Enhancing the credibility of a 30 km/h urban speed limit through road design

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By

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Executive summary

This thesis investigates how road design can enhance the credibility of a 30 km/h speed limit, particularly in the context of urban distributor roads in the Netherlands transitioning from GOW50 (50 km/h) to GOW30 (30 km/h). The motivation stems from increasing urbanisation, high levels of pedestrian and cyclist activity, and growing concerns about road safety, especially for vulnerable road users. While lowering speed limits is a common strategy to improve safety, such limits must be credible, meaning they align with driver expectations formed by the road's visual and structural characteristics.

The study addresses three core research questions: (1) What factors influence the credibility of a speed limit? (2) How do various road design characteristics affect actual driving speeds? and (3) How do these characteristics shape drivers' perceptions of speed limit credibility and safety? To answer these, a mixed-methods approach was applied. A conceptual framework was developed from the literature, real-world speed data from 30 Dutch urban road segments were analysed using t-tests, ANOVA, and general linear models (GLM), and survey responses from 83 participants were assessed using descriptive statistics, chi-square tests, and ordinal logistic regression.

Key findings reveal that road design significantly influences both actual driving speeds and perceptions of speed limit credibility. Characteristics such as lane width, road surface, presence of lane markings, and the type of bicycle facilities each contribute in varying degrees to speed choice and perceived appropriateness of speed limits. Notably, roads with narrower lanes, brick surfaces, no lane markings, and separated bike lanes were associated with lower speeds and higher 30 km/h speed limit credibility. The study also highlights that credibility perceptions differ across road types and speed zones, underlining the importance of design consistency with speed policies.

The thesis makes several theoretical contributions by empirically connecting speed limit credibility to specific road design elements and by extending the concept of self-explaining roads. Practically, it informs policymakers and traffic engineers on how to design roads that intuitively communicate safe driving speeds. It supports a shift toward design-led speed management, especially in cities implementing Vision Zero strategies. Recommendations include integrating credibility-enhancing features into the GOW30 design standards and prioritising infrastructure that aligns with drivers' expectations of safe and appropriate speeds.

1. Introduction

1.1. Research context

The urban landscape is constantly evolving, presenting a range of challenges and opportunities for transportation planners, engineers and policy makers. Among the most pressing concerns is the need to ensure road safety while accommodating an increasingly urbanised society and facilitating efficient mobility. The dense and compact nature of many cities around the world, and particularly those in Europe, allow for multi-modal transportation to flourish and encourages a stronger shift away from automobile dependency. This results in a wide mix of road users, with many cities having a relatively high percentage of pedestrians and cyclists. In Amsterdam for example, cycling makes up about 32 percent of total journeys within the city, while walking makes up about 29 percent (Deloitte, 2018). However, 20 percent of journeys in the city are still done by car. The prevalence of car use within urban areas pose a risk towards pedestrians and cyclists, especially if there are limited legal and infrastructural provisions that ensure the safety and protection of vulnerable road users from high-speed motor traffic.

In recent years, increasing scrutiny has been placed on the issue of road safety for vulnerable road users, particularly in an urban context where there are high concentrations of pedestrians and cyclists. In the Netherlands, cyclists make up about 39 percent of all road fatalities in the country, the largest share out of any other road user group (SWOV, 2023). Car drivers make up about 30 percent of road fatalities, followed by pedestrians at 8 percent. Furthermore, 41 percent of all road deaths occur within urban areas, and around two-thirds of those deaths occur on roads with a 50 km/h speed limit. In light of these statistics, many cities and municipalities in the Netherlands, as well as others around the world, are pursuing measures aimed at reducing the number of road fatalities and improving safety overall for all road users.

One of the more common approaches taken by local authorities to address the road safety issue is to reduce the urban speed limit from 50 km/h to 30 km/h. In December 2023, the municipality of Amsterdam reduced the speed limit on most urban roads from 50 km/h to 30 km/h, increasing the percentage of streets with a 30 km/h speed limit from 70 to 82 percent (Röth, Koljensic and Kuipers, 2022). Other cities in the Netherlands have plans to roll out the 30 km/h urban speed limit in phases. These measures are all part of a national push to make roads safer by lowering the speed limit on so-called "*gebiedsontsluitingswegen*" (abbreviated as GOW). These are essentially distributor roads that primarily have a traffic flow function, as opposed to "*erftoegangswegen*" (abbreviated as ETW) which are access roads that primarily have a residential function (CROW, 2021). Roads categorised as ETW have a default speed limit of 30 km/h (known as ETW30), while roads categorised as GOW typically have a default speed limit of 50 km/h (known as GOW50). The recent push to improve road safety in the Netherlands has led to the introduction of a new road category, known as GOW30, and these are distributor roads that have both a traffic flow function and a residential function (which is already the case for many urban roads in the Netherlands). Therefore, in order to balance these functions effectively by ensuring traffic flow while also maintaining liveability and safety standards for local residents, these roads are set to a 30 km/h speed limit. As a result, many GOW50 roads are transitioning to GOW30 in the coming years, and this transition will be the main focal point of this thesis moving forward.

1.2. Research problem

The justification for this speed limit reduction from GOW50 to GOW30 is that the risk of a fatal accident is very low at speeds of or below 30 km/h (SWOV, 2018). However, the mere installation of 30 km/h signage represents only a preliminary step in the transition from GOW50 to GOW30. Establishing a 30 km/h speed limit necessitates adherence from drivers, and whether or not drivers adhere to the speed limit is impacted, directly or indirectly, by the credibility of the speed limit. Hence, a challenge for urban planners and policy makers arises: How can these urban roads be re-imagined and redesigned, incorporating measures that not only substantially increase drivers' compliance but also make the new speed limit credible?

The effects of speeding on overall road safety have been extensively researched, and there is a general consensus among experts that high vehicle speeds is a leading factor in the frequency and severity of road accidents (SWOV, 2021; Lu, Qurashi and Antoniou, 2023; Son et al., 2022). A body of research looking into the effects of speed limit reductions generally results in positive outcomes for road safety overall. However, reducing the speed limit on its own is not effective enough in incentivizing a long-term change in driving behaviour, as the speed limit would have to be credible and justifiable in order to stimulate such a change. As a result, paradigms and approaches to speed management are beginning to shift from just merely utilising legal instruments to enforce speed limits, to exploring the implementation of physical road design features that are self-explanatory and would effectively influence driving behaviour. Research shows that these self-explanatory road design interventions can be effective in inducing slower speeds and therefore improve speed limit compliance. However, a speed limit can only be considered credible if it matches the design and the layout of the road, and thus it is heavily dependent on the perception of drivers. This thesis will attempt to address this research gap pertaining to the credibility of a 30 km/h urban speed limit, especially in the context of GOW30 in the Netherlands, by examining the role of road design in people's perceptions and attitudes towards speed limits. The central focus of this thesis lies in identifying effective road design strategies that bolster the credibility of GOW30 while encouraging and ensuring increased compliance among drivers, with the ultimate aim of improving road safety for all road users and ensuring a smooth and successful transition from the 50 km/h urban speed limit to a 30 km/h one.

1.3. Research questions

The objective of this study is to investigate the effectiveness of various road design characteristics on bolstering the credibility of a 30 km/h urban speed limit, particularly in the context of GOW30. The outcome of this study can then be used as an advisory tool to aid urban planners and policy makers in making socially responsible infrastructure policy decisions as cities in the Netherlands, and around the world, begin to transition from a 50 km/h urban speed limit to a 30 km/h one, with the ultimate goal of reducing road fatalities and improving liveability for local residents. The main research question is formulated as follows:

What road design characteristics are the most effective at enhancing the credibility of GOW30?

Three sub-questions have been defined to aid in the answering of the main research question. The sub-questions are as follows:

1. *Based on literature, what factors influence the credibility of a speed limit?*
2. *What are the effects of various road design characteristics on actual speeds being driven on urban roads?*

3. *What are the effects of various road design characteristics on drivers' perceptions towards speed limit credibility and risk?*

1.4. Report structure

The report is structured as follows: First, the methodology of the research is presented, in which the data collection and analysis methods for each sub-research question are discussed. Next, a literature review consisting of previous studies on speed limit reduction effects, road design strategies, perceptions towards speed limits and speed limit credibility factors are explored, concluding with a conceptual framework discussing all the factors that influence speed limit credibility (and thus providing an answer to the first sub-question). Following the literature review, the results of the analysis are presented. The results are divided into two main sections: The analysis of vehicle speeds on roads with varying characteristics (second sub-question), and the analysis of drivers' perceptions towards speed limit credibility and safety (third sub-question). Finally, a discussion on the study's theoretical contributions, practical implications, research limitations and future research recommendations are presented, followed by the conclusions of the study.

2. Methodology

2.1. Overview

In this section, the methodology employed for this research is presented. In order to answer the main research question effectively, a mix of quantitative and qualitative methods were used. Each method was chosen based on how appropriate and relevant a method is for answering a specific sub-question. Therefore, for each sub-question there is a corresponding method for answering that specific sub-question. Table 2.1 shows an overview of the sub-questions and their corresponding collection and analysis methods. The presented methods are discussed in more detail in the following sections.

Table 2.1. Overview of methods.

Sub-question	Data collection method	Data analysis method
1. *Based on literature, what factors influence the credibility of a speed limit?*	Literature review	Development of a conceptual model
2. *What are the effects of various road design characteristics on actual speeds being driven on urban roads?*	Speed and traffic data extracted from Telraam (open-source traffic database)	Analysis of descriptive statistics regarding road characteristics and average V85 speeds on selected road segments; utilisation of t-tests, linear regression and ANOVA to determine statistical differences in mean speeds between different road types
3. *What are the effects of various road design characteristics on drivers' perceptions towards speed limit credibility and risk?*	Online survey regarding speed limit perception, perceived safety and speed limit credibility perception	Analysis of descriptive statistics regarding perceived safety and speed limit credibility perception of certain road types; utilisation of chi-square tests and ordinal logistic regression to determine statistical significance of the credibility of different road types

2.2. Data collection

For each sub-question, a variety of methods were used to collect meaningful data pertaining to the respective sub-question. For the first sub-question, the main data collection method was through means of a literature review. The purpose of a literature review is to gain a deeper understanding of the various societal, environmental and psychological factors that determine the credibility of a posted speed limit, and how this is intertwined with road design. Furthermore, a literature review will contribute to a greater insight into existing road design strategies currently implemented for various urban road types, and how each design differs from one another based on road function and speed limit. The literature review examines the impacts of speed limit reductions on vehicle speeds and crash rates, impacts of road design interventions on driving behaviour, and the perceptions and attitudes of drivers toward lower speed limits. The findings from the literature review culminates in a conceptual framework linking all the factors and variables affecting speed limit credibility, thus providing and answer to the first sub-question (see Section 2.3 for further details).

In order to answer the second sub-question, data about actual speeds being driven on certain road types were collected. This was done by extracting vehicle speed data on specific road segments from the open-source traffic database known as Telraam, which is a database that stores data on a variety of traffic-related parameters such as average (85^{th} percentile, or V85) speeds per time of day, modal share and traffic counts. This data is collected through citizen participation in which individuals set up a device on their window facing the street, and the device records traffic movements and speeds along that particular street throughout the day and uploads that data to a cloud server in real time. Data on hourly average V85 speed distributions were primarily collected from selected street segments with varying street designs in order to ensure a representative overview of the actual speeds driven on roads with different designs. The selection of road segments, the type of road design characteristics examined and the operationalisation of the Telraam data are discussed in more detail in Section 2.4.

For the third sub-question, an online survey was conducted in order to gain insight into the perception of drivers regarding the credibility of speed limits on certain road sections, and in particular to determine whether or not they perceive a given speed limit to be appropriate for a given road design. The survey included questions regarding demographic characteristics of the respondent (age, gender, nationality), driving experience (possession of driver's license, years of experience, car ownership), and a set of eight scenarios depicting various road designs in which respondents were asked to assess what they think the speed limit is on a particular road (without knowing what the actual speed limit is), their perceived risk when driving at a particular speed, and whether or not they perceive a 30 km/h (or 50 km/h) speed limit to be appropriate for that particular road design. These questions were a mix of multiple choice (e.g. 30 km/h or 50 km/h) and Likert scale ranking (e.g. (1) not credible at all, to (5) very credible). The survey was created using MS Forms, with an initial goal of receiving around 50 responses to ensure that enough data can be analysed and that sound conclusions can be drawn regarding speed limit credibility as a function of road design. Ultimately, a total of 83 responses were collected through a mix of survey platforms (the SurveyCircle and SurveySwap platforms were used to distribute the survey and collect responses) and through personal and professional networks. More details about the survey are discussed in Section 2.5.

2.3. Data analysis

The analysis of the data collected for each sub-question involved a mix of qualitative and quantitative approaches. The first sub-question is primarily answered through qualitative means while the second and third sub-questions are answered through quantitative means. For the first sub-question, a conceptual model was developed in order to show and visualize the relationships between the factors that influence the credibility of a speed limit, and how these factors are influenced by road design. Such factors include perceived safety, road environment, speed limit compliance, and driving behaviour, among others. As mentioned previously, identifying and linking these different factors largely comes from existing literature pertaining to speed limit credibility. The conceptual model helps to further refine the definition of credibility used in the context of this thesis, and also contributes to the framing of survey questions intended to produce the most representative results of drivers' perceptions regarding speed limit credibility.

After the road segments have been selected for analysis and the V85 speed data from Telraam is collected for the second sub-question, an initial analysis of the descriptive statistics regarding the distribution of road segment characteristics and the distribution of vehicle speeds was conducted. V85 speeds were analysed and compared between 30 km/h and 50 km/h road segments, in order to gain a preliminary understanding of the actual speeds driven on certain road types and how certain characteristics may influence driving speeds. To fully understand and determine the extent to which these characteristics have a significant effect on driving speeds, statistical hypotheses testing was carried out. The type of statistical test used in the analysis depended on the nature of the road characteristic being tested, which resulted in wide mix of statistical methods used in the analysis, including two-sample t-tests, Analysis of Variance (ANOVA), and linear regression. Each road characteristic was tested individually to determine their standalone effects on vehicle speed. Additionally, a General Linear Model (GLM) was constructed to determine the effects of these road characteristics in conjunction with one another on vehicle speed. These tests were carried out and its results were analysed using IBM's SPSS statistical software.

The same approach was taken for the analysis of the third sub-question as was done for the second sub-question. After all the survey responses was collected, a preliminary analysis of the survey results was conducted by examining the descriptive statistics of the responses from the survey, including the demographic characteristics of the respondents. Following the descriptive analysis, hypothesis testing was also conducted to determine the extent in which certain road characteristics significantly influence the perception of drivers regarding safety and the credibility of a speed limit. Since the dependent variable (perception of safety and credibility) in this case is categorical and rank-based, Ordinal Logistic Regression was used for this analysis. The results of this test was then corroborated together with the results of the analysis from the previous sub-question in order to gain a holistic understanding of the relationship between speed limit credibility and actual driving speeds, and would therefore contribute to the answering of the main research question.

2.4. Case selection

In order to collect speed and traffic data for the analysis of the second sub-question, a selection of 30 Dutch urban street segments from the Telraam database were used as case studies, each with varying design characteristics so that a representative sample of road designs can be achieved. For each street segment, raw data on hourly V85 speeds (within a given timeframe) were extracted from the Telraam API. Additionally, dominant design characteristics for each segment were manually identified and aggregated with the rest of the data, in order to enable the analysis of the effects of certain road characteristics on vehicle speeds. Because of the many characteristics that ultimately defines the design of a specific road, only a selection of characteristics were used for analysis. Some of these characteristics were derived from literature in which their effects on speed have been well-established, as well as particular characteristics that are common and unique to the Netherlands, such as bicycle lanes. Table 2.2 shows some common road characteristics and their effects on driving speed.

Table 2.2. Road characteristics and their effects on driving speed (SWOV, 2021).

Road characteristic	Effect of driving speed
Number of lanes	More lanes → higher speed
Road/lane width	Wider roads/lanes → higher speed
Median	Median present → higher speed
Hard shoulder	Hard shoulder present → higher speed
Longitudinal marking	Edge and centre line marking → higher speed
Road surface	Smooth road surface (asphalt) → higher speed
Open environment	Open environment → higher speed

For the analysis, the following road characteristics were examined:

- Official speed limit (linked with road category)
- One-way/bi-directional implementation
- Road/lane width
- Presence of longitudinal markings
- Type of road surface (asphalt or brick)
- Presence of bicycle lanes and nature of separation (dedicated, gutter or none)
- Presence of on-street parking

The presence of hard shoulders and the nature of the environment (whether it is open or closed) were not examined due to the fact that hard shoulders are not characteristic of GOW (and ETW) in urban areas, and because the analysis was focused on urban roads, the environment is closed in nature (due to the built-up surroundings).

As for the case selection, the following street segments were analysed (images of the road segments can be found in Appendix B):

- Westplantsoen, Delft
- Proveniersplein, Rotterdam
- Fluwelensingel, Gouda
- Rijnstraat, Woerden
- Albatrosstraat, Utrecht
- Wittevrouwensingel, Utrecht
- Weerdsingel Westzijde, Utrecht
- Hopakker, Utrecht
- Draaiweg, Utrecht
- Nieuwendammerdijk, Amsterdam
- Adriaan Loosjesstraat, Amsterdam
- Beemsterstraat, Amsterdam
- Meerpad, Amsterdam
- Vogelenzangseweg, Vogelenzang
- Utrechtseweg, Amersfoort

- Vlasakkerweg, Amersfoort
- Noordewierweg, Amersfoort
- Bisschopsweg, Amersfoort
- Eemnesserweg, Baarn
- Drakenburgerweg, Baarn
- Plataanlaan, Baarn
- Zandstraat, Veenendaal
- Kanaalweg, Veenendaal
- Munnikenweg, Veenendaal
- Hugo de Grootstraat, Arnhem
- Heijenoordseweg, Arnhem
- Brouwerijweg, Arnhem
- Spijkerstraat, Arnhem
- Geestersingel, Alkmaar
- Gabriël Metsulaan, Eindhoven

In order to obtain reliable data, road segments were chosen based on the volume of traffic per hour within a given timeframe. Road segments with relatively moderate volumes of motor traffic were selected as they represent normal (free flow) traffic conditions and therefore provides a reliable amount of data on typical driving speeds. Road segments with relatively low or high traffic volumes were not selected as they may result in a lack of speed data (on roads with low traffic volumes) or speed data that do not represent free flow conditions (particularly on roads with heavy traffic resulting in congestion). The selected road segments have average traffic volumes of 100 to 200 (car) movements per hour (considered to represent moderate traffic conditions), and were measured in the time period between 07:00 and 11:00 on a typical weekday (measurements were taken during the week between July 1st and July 5th, 2024). This is represented by the darker (purple) coloured dots on the Telraam map, as shown in Figure 2.1.

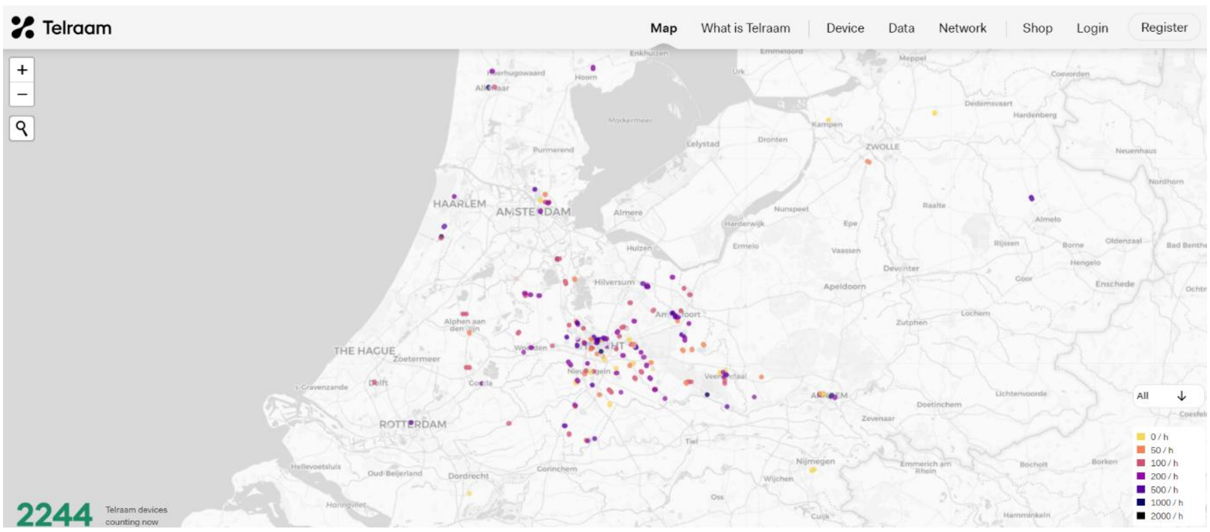

Figure 2.1. Telraam interface showing locations of operational Telraam devices. Darker coloured dots represent higher traffic volumes measured.

In addition to traffic volumes, road segments were also chosen based on road design variations. These included variations in speed limits, road surfaces, bike lane configurations, lane widths, and so forth. By having enough variation in road designs within the case selection, it ensures that most of the predominant road design variations in the Netherlands are represented in the sample, and it allows for more precise measurements of the effects that various road characteristics have on vehicle speeds. To achieve this, road segments were selected from a mix of major urban areas (such as Amsterdam and Utrecht) and small- to medium-sized towns (such as Amersfoort and Baarn). Because the focus of this analysis is on urban roads, road segments located outside of urban/built-up areas (i.e. country roads) were not taken into consideration, and were therefore not included in the sample.

2.5. Survey questionnaire

As mentioned previously, a survey was conducted in order to collect data on drivers' perceptions towards speed limit credibility and risk. The survey was chosen as the primary data collection method for the analysis of the third sub-question, given the subjective nature of risk and credibility perception. The responses given in the survey allows for a better understanding of how people perceive different speed limits, how people perceive risk and how road design influences those different perceptions, among other factors. These perceptions would, in turn, provide a benchmark for determining whether or not a speed limit is considered to be credible for a particular road design.

The survey was created using MS Forms and was distributed digitally through survey platforms such as SurveyCircle and SurveySwap, as well as through professional and personal channels. The survey was mainly targeted towards adults living in the Netherlands (Dutch and non-Dutch residents), due to the contextual nature of the survey questions being based on Dutch roads. The survey was conducted over a span of a month throughout August 2024. A total of 83 responses were received from the survey, which was considered to be a sufficient number of responses in order to conduct a concrete analysis of the relationships between road design and people's credibility and risk perceptions. For ethical and privacy reasons, the survey responses were anonymous and no personally identifiable information were asked in the survey (such as names and contact details), therefore not a single response can be traced back to a specific individual. The survey itself and the data management plan associated with the survey had been reviewed and approved by the Human Research Ethics Committee (HREC) of TU Delft prior to distribution, meaning that the survey conformed to ethical and data privacy guidelines stipulated by the HREC as well as any national or European laws concerning data protection (such as the GDPR of the European Union).

The survey began with a brief introduction of the topic of speed limit credibility, as well as a brief explanation of how the survey is structured. The survey consists of two parts: The first part consists of 7 multiple choice questions regarding demographic characteristics, travel preferences and driving experience, while the second part consists of 8 scenario-based questions, each consisting of 3 sub-questions asking respondents to assess, based on a given still image of a road segment, their perception of what the speed limit is for that particular road segment (without knowing what the actual speed limit is), their perception of how safe they feel when driving or cycling on that road according to a given speed limit, and their perception of how credible they think a 30 km/h or 50 km/h speed limit is based on how the road is designed. The first part consists of questions such as:

- Age (within a given range)
- Gender (male/female/other)
- Preferred mode of transport (list of options including car, bike, public transport, etc.)

- Possession of a driver’s license (yes/no)
- Years of driving experience* (within a given range)
- Driving frequency* (daily, weekly, monthly, etc.)
- Car ownership* (yes/no)

The questions marked with an asterisk (*) were only answered by respondents who have indicated that they are in possession of a driver's license (those who have indicated ‘no’ were not shown those questions).

The second part of the survey comprises of 8 different road design scenarios with varying speed limits (i.e. 30 km/h and 50 km/h) and varying road characteristics (e.g. different road surfaces, bike lane configurations, lane widths, etc.), which were chosen from the list of road segments as shown in Section 2.4. The road segments selected for the survey were:

- Proveniersplein, Rotterdam
- Draaiweg, Utrecht
- Beemsterstraat, Amsterdam
- Weerdsingel Westzijde, Utrecht
- Rijnstraat, Woerden
- Drakenburgerweg, Baarn
- Fluwelensingel, Gouda
- Nieuwendammerdijk, Amsterdam

For each of these road segments, respondents were asked the following questions:

1. What do you think is the speed limit on this road? (Choice of 30 km/h, 50 km/h, or manual input)
2. How safe would you feel travelling (by car or by bike) on this road at the given speed limit? (Likert scale ranking from ‘very unsafe’ to ‘very safe’ for speed limits of less than 30 km/h, 30 km/h, 50 km/h and more than 50 km/h)
3. How credible do you perceive the following speed limits to be for this road? (Likert scale ranking from ‘not credible at all’ to ‘very credible’ for speed limits of 30 km/h and 50 km/h)

The responses from these questions were used as the primary input for the analysis of people’s perceptions towards speed limit credibility and safety, hence the use of a Likert scale as a measurement of how people perceive speed limits and risk differently based on how a road is designed. The full survey can be found in Appendix C.

3. Literature review

With the increase in car ownership and urban population density over the past few decades, and a continuation of this trend in the years to come, road safety has become a major concern for local and national authorities worldwide. As a result, extensive research on road safety issues have been conducted by researchers around the world, and the outcomes of such studies have provided a foundation for traffic engineers, urban planners and transport policy decision-makers to make sound decisions and policy choices in order to improve safety for all road users and reduce the occurrence and severity of accidents. As many studies have shown, speeding is the leading contributor to the number and severity of road accidents worldwide, particularly in urban areas (SWOV, 2021; Lu, Qurashi and Antoniou, 2023; Son et al., 2022). In general, it is understood that the higher the average speed of a vehicle is, the higher the crash risk will be, and in turn the risk of serious injury or fatality also increases. In light of these findings, road authorities around the world are utilising various means and measures to reduce the average traffic speeds in urban areas, most commonly by reducing posted speed limits on certain road segments or even for whole areas, such as residential neighbourhoods or places with high pedestrian activity (i.e. city centers).

3.1. Measuring effects of speed limit reductions

Many studies have looked into the impacts of a speed limit reduction on road safety overall, by means of various methods. A study conducted by Lu, Qurashi and Antoniou (2023) explored the effects of different speed limit scenarios on road safety, traffic efficiency and the environment, through the use of simulation models. The main purpose of the study was to develop a comprehensive framework that integrates traffic simulation tools with policy analysis techniques, which can then be generally applied as a methodological approach for assessing the implications of changing speed limits in urban areas. The authors argue that traditional analytical methods often lack the capacity to capture the complex dynamics of urban traffic systems comprehensively, therefore opting for simulation-based policy analysis as a more holistic approach to determine the effects of speed limit policy changes on a range of indicators, such as pedestrian safety, travel time and exhaust emissions (Lu, Qurashi and Antoniou, 2023). The framework was applied to simulate different speed limit scenarios in the city center of Munich, Germany, and it was found that speed limit reductions can significantly improve road safety and reduce environmental externalities, at a relatively minimal expense to traffic efficiency.

A study conducted by Gressai et al. (2021) takes a similar approach: Microscopic traffic simulation was used to investigate the effects of urban speed limit reductions on traffic flow, travel times and vehicle emissions. Microscopic traffic simulation models simulate individual vehicle movements and interactions, therefore factors such as road geometry, traffic volume, driver behaviour and signal timings are taken into account. Unlike the simulation framework developed by Lu, Qurashi and Antoniou (2023), the model utilised by Gressai et al. does not include any policy evaluation techniques, therefore the analysis of urban speed limit reductions in this study may not be as holistic or comprehensive. There is also less of a focus on safety and more emphasis on traffic flow and emissions. The study was conducted in Budapest, Hungary, and the simulation model was applied to two road network types: A downtown network with a speed limit reduction from 50 km/h to 30 km/h, and an urban arterial road with a speed limit reduction from 70 km/h to 50 km/h (Gressai et al., 2021). The results of the simulation are mixed, with an increase in emissions on roads with a 50 to 30 km/h speed limit reduction and a slight reduction in emissions on roads with a 70 to 50 km/h speed limit reduction. The results also show that travel times will generally increase but traffic volumes will remain largely unaffected by the speed limit reductions.

Like the previous two studies, a study conducted by Cohen, Christoforou and Seidowsky (2014) also employed a simulation technique to research the impacts of a speed limit reduction on average speeds and emissions. However, it differs from the previous studies in which the authors apply a macroscopic traffic simulation model to investigate speed limit reduction effects. Unlike microscopic traffic simulation, as was used by the other authors in which it models individual vehicle movements and complex traffic interactions, macroscopic traffic simulation models traffic dynamics at an aggregate level, typically used to model overall traffic density, speed and flow at a larger spatial and temporal scale than microscopic traffic simulation (Mohan and Ramadurai, 2013). The output of the macroscopic traffic simulation model is therefore much more deterministic in nature as it does not account for individual driving behaviour. The model was applied to simulate traffic conditions on several urban motorways in Lille, France, in which the speed limit was reduced from 110 km/h to 90 km/h (Cohen, Christoforou and Seidowsky, 2014). The study concluded that the speed limit reduction would lead to an overall decrease in average speeds and a reduction in emissions, which is expected and in line with the findings of other similar studies.

While some studies, such as the ones previously discussed, utilise simulation techniques to investigate the impacts of speed limit reductions, other studies utilise a set of various methods to achieve the same research objectives. A study conducted by Son et al. (2022) investigated the direct and indirect effects of an urban speed limit reduction on vehicle and pedestrian safety, by developing a set of crash modification factors (CMFs) that would estimate the expected change in the frequency of crashes after a set of safety treatments are applied to specific road segments (the safety treatments in this case are the speed limit reductions). The CMFs are estimated using various methods, such as the cross-sectional method, the naïve before-after method and the Empirical Bayes method (Son et al., 2022). The study was conducted on urban roads in South Korea, and CMFs were calculated for road sections with a speed limit reduction from 60 km/h to 50 km/h (direct effects), as well as for adjacent road sections without the speed limit reduction (indirect effects). The results of the study revealed that the speed limit reduction contributed to a significant safety improvement in terms of the number and severity of crashes, on both the treatment sections and adjacent sections, meaning that the speed limit reduction does not only have positive direct effects but also positive indirect effects within the surrounding environment.

A different study, conducted by Schaefer, Figliozzi and Unnikrishnan (2022), utilised a series of statistical hypothesis tests to analyse the effect of a 5 mph speed limit reduction on vehicle speeds in Portland, Oregon. Unlike the other studies discussed previously, this study had a particular focus on cyclists' safety, therefore the study was largely conducted on urban roads with a high percentage of cyclists (>15% of total traffic composition). The authors wanted to evaluate the effectiveness of speed limit reductions in improving cyclist safety and promoting multi-modal transportation, and conducted a before and after analysis of traffic speeds on roads that underwent a 5 mph speed limit reduction (treatment sites) and on roads without the speed limit change (control sites). They also make a distinction between neighbourhood greenways (residential streets with mixed traffic) and non-greenways (urban roads with predominantly motor traffic), and compare the effects between the two road types. The statistical tests were used to determine whether there were significant differences in mean speeds, 85th percentile speeds, speed variances and proportion exceeding speed thresholds between the before and after speed limit reduction scenarios, and found that, albeit with a high degree of variability, there were generally more significant decreases in speed characteristics within the treatment group compared to the control group, and even more significant decreases on roads classified as neighbourhood greenways as compared to non-greenways, implying that a speed limit reduction can meaningfully contribute to an improvement towards cyclist safety (Schaefer, Figliozzi and Unnikrishnan, 2022).

While the bulk of research into the safety effects of a speed limit reduction primarily concentrated on individual road segments and selected areas, few research has been conducted looking into the safety effects of a blanket speed limit reduction on a citywide scale. A study conducted by Zhai et al. (2022) attempted to address this gap in research by assessing the effect of a citywide speed limit reduction on the frequency of crashes in New York City. In 2014, the default speed limit on New York City roads without a posted speed limit was reduced from 30 mph to 25 mph, which motivated the authors to investigate the impact that it had on pedestrian and traffic safety. To account for confounding bias and spatial spillover effects, which arose as a result of a lack of sufficient control sites and the city's high density road network respectively, the authors propose a novel causal inference approach that integrates propensity score matching and the spatial difference-in-differences method to estimate the safety effectiveness of the citywide speed limit reduction (Zhai et al., 2022). The study found that the speed limit reduction significantly decreases the occurrence of fatal crashes by 62%, but has little impact on the number of injury crashes and property-damage-only crashes.

3.2. Measuring effects of road design interventions

Up until this point, the studies that have been discussed primarily focused on reducing urban speed limits as a tool to reduce vehicular speeds and, in turn, improve safety for all road users involved. However, a speed limit reduction on its own would not be sufficient in order to encourage and enforce a change in driving behaviour. Even though many studies have shown that a speed limit reduction does in fact reduce average speeds and improve road safety overall, there is still a high potential for speeding if no other speed-reducing measures are put in place. In recent years, more attention has been directed towards road design and infrastructural elements, and how they can be manipulated to influence driving behaviour and reduce speeding.

Just like with speed limit reductions, an abundance of research went into the effects of road design on vehicle speeds, driving behaviour and overall safety. One such study, conducted by Martinelli et al. (2022), looked into the effects of certain road characteristics on vehicle speeds along several urban road segments in the town of Brescia, Italy. Road characteristics such as the number of lanes, road geometry, presence of medians, bus stop density and land use patterns were examined, and speed data was collected by using laser traffic counters that were placed along selected road segments. Multiple linear regression models were used to estimate mean speed and speed dispersion parameters for the corresponding road segments, and the statistical significance of the relationship between vehicle speed and the road characteristics of each surveyed road segment was tested. It was found that certain characteristics such as lane width, presence of a median, bus stop density, pedestrian crossing density, presence of sidewalks, and adjacent land use patterns (particularly residential, commercial and the presence of schools) play a significant role in explaining the speed distribution along those segments (Martinelli et al., 2022). While some characteristics, such as land use patterns, contribute to a reduction in mean speeds, other characteristics, such as increasing lane width, median presence and sidewalk presence, contribute to an increase in mean speeds, leading to both expected and unexpected outcomes.

A similar study was done by Schano, Novy and Smisek (2023), in which they examined infrastructural elements that affect driving speeds within built-up areas in the Czech Republic. The set of infrastructure elements examined in this study is almost identical to those examined by Martinelli et al. (2022), including elements such as lane width, road curvature, bus stop density, pedestrian crossing density, and usage of road markings. Vehicle speeds were measured using a microwave traffic detector that was placed alongside selected road segments across various municipalities in the Czech Republic. To establish whether or not there are any correlations between the examined roadway elements and driving speeds, as well as to determine the strengths of those correlations, the authors used the Spearman correlation coefficient. There are some similarities in the findings from this study and the findings of Martinelli et al. (2022), such as the finding that bus stops play a crucial role in reducing driving speeds. However, there are also some contrary and unexpected findings, such as the finding by Schano, Novy and Smisek (2023) that lane width did not have a significant effect on driving speed. It was also found that the presence of a pedestrian crossing is not a significant factor in reducing speeds. The differences in findings may be attributed to the slight differences in data collection and data processing techniques used by both studies, as well as the contextual differences in which the two studies were carried out.

A study conducted by Mackie et al. (2013) investigated the effects of specific road design interventions on the behaviour of road users. This study takes a slightly different approach than the one taken by Martinelli et al. (2022) and Schano, Novy and Smisek (2023): Rather than examining road characteristics typically associated with conventional road design, Mackie et al. looked into the effects of purposefully-tailored road design interventions that aim to evoke correct expectations and driving behaviours from road users, in which they call the "self-explaining roads" (SER) approach. This approach is intended to improve safety for all road users by focusing on the functionality, homogeneity and predictability of the road network (Mackie et al., 2013). The study also had less of a focus on actual speeds driven before and after an SER intervention, and more of a focus on the actions and behaviours of both drivers and pedestrians as a result of an intervention (lane keeping, turning behaviour, crossing behaviour, etc.). SER interventions that were examined in this study, which was conducted in a suburb of Auckland, New Zealand, included a central island built before a local intersection, a roundabout constructed on a local intersection, and a painted bicycle lane along a collector road. Data was collected through video recordings of the treatment sites to observe road user behaviour before and after an SER intervention, as well as road user counts to measure activity before and after the intervention. The study found that pedestrian activity increased on local roads post-intervention, as well as a decrease in through traffic on those roads (Mackie et al., 2013). In terms of driving behaviour, it was found that there was less uniformity in lane keeping and less indicating by drivers on local roads. These behaviours were not observed on collector roads, however.

3.3. Perceptions and attitudes towards lower speeds

Speed limit reductions and road design interventions have proven to be effective ways to induce lower driving speeds. However, the speed at which a driver chooses to drive is ultimately dependent on their individual driving behaviour and what they perceive to be a safe driving speed. Perceptions vary from person to person, and they may depend on a variety of factors such as driving experience, age and personality traits. A planned speed limit reduction or road design change may elicit a strong public reaction if it is not perceived to be justified, even if there is strong evidence that such changes will provide net safety and environmental benefits for the local community. Therefore, it would be in the interest of policy makers to gain an understanding of the public's perceptions and attitudes towards measures designed to reduce driving speeds in certain areas, which would allow policy makers to determine whether or not the implementation of a speed-reduction measure is socially justified, and whether these measures can be further targeted to induce slower driving among people that exhibit speeding behaviour.

One study in Australia, conducted by Lahausse et al. (2010), examined people's attitudes and perceptions towards current speed limits as well as proposed speed limit reductions. The authors wanted to investigate the level of public willingness to accept lower speed limits on certain road types, and determine what demographic and socioeconomic factors influence people's opinions regarding speed limits in general. An online survey was carried out, which asked respondents questions regarding their socioeconomic characteristics, their knowledge about speed limits on certain road types (residential, urban and rural), their driving behaviour on those roads and how they felt about the current speed limits (whether it's too high, too low or just right). The respondents were also asked about their opinions regarding a lower speed limit for each road type. The survey found that most of the respondents favoured lower speed limits for rural roads but did not particularly favour lower speed limits for urban and residential roads, as they thought that the speed limits currently set for those road types were already appropriate (Lahausse et al., 2010). The study also revealed that females living in urban areas were more likely to support lower speed limits than males living in rural areas, and people over the age of 56 tend to have less favourable attitudes towards speed limits in general, which is a contrast to other studies finding that younger people are the ones with less favourable attitude towards speed limits.

A similar study was conducted in Japan, but with a focus on urban residential streets with a 30 km/h speed limit. Dinh and Kubota (2013) investigated the perceptions and attitudes of Japanese drivers towards the 30 km/h speed limit on residential streets, in which they, like Lahausse et al. (2010), employed a survey to gain insight into public perception and level of support for the 30 km/h speed limit. The survey included questions about speeding behaviour among drivers, their opinions and attitudes towards complying with or exceeding the 30 km/h speed limit, their perceptions regarding the opinions of local residents and other road users, and what factors influence their chosen driving speed, along with questions about demographic characteristics. Furthermore, logistic regression models were developed to determine demographic and behavioural factors that influence the level of support or opposition towards the 30 km/h speed limit. Based on the results of the survey, the study found that the majority of respondents were supportive of the 30 km/h speed limit on residential streets, although speeding was found to be a common occurrence among the respondents (Dinh and Kubota, 2013). Many respondents reported that compliance with the 30 km/h speed limit is dependent on a street design which would make the speed limit credible. It was also found that there was a tendency among respondents who had unfavourable views towards the 30 km/h speed limit to have committed traffic-law violations in the past, were less sympathetic towards the opinions of residents and vulnerable road users, and had difficulty refraining from speeding.

Lastly, a study in Israel investigated the role of street design on drivers' perceptions of appropriate speeds. The study, conducted by Gitelman, Pesahov and Carmel (2020), combined methods employed by the likes of Lahausse et al. (2010) and Dinh and Kubota (2013) to investigate people's perceptions regarding speeds and speed limits, together with methods that were used to determine relationships between road design and actual speeds driven, employed by the likes of Martinelli et al. (2022) and Schano, Novy and Smisek (2023). To gain an understanding of driver perceptions, a survey was conducted which asked drivers in Israel about what they deem appropriate speeds to be driven on certain urban road segments. This was complemented by field surveys which collected data on road design characteristics and actual speeds driven along those road segments, in addition to data about traffic and pedestrian volumes on those segments. Multivariate regression models were developed to examine relationships between road characteristics and driving speeds, and it was found that the road layout was a significant factor for drivers in selecting an appropriate driving speed. For example, drivers perceived higher speeds to be more appropriate on multi-lane carriageways while lower speeds were more appropriate for single-lane carriageways and one-way streets. Additionally, road segments with high levels of pedestrian activity, high degree of visual lane narrowing and the presence of non-signalised intersections also contributed to drivers' perceptions that lower speeds were more appropriate on those segments, and therefore the actual speeds driven were in accordance with what drivers perceived to be an appropriate speed for that particular road segment.

3.4. Factors influencing speed limit credibility and conceptual framework

The majority of studies in the field of road safety primarily examine the effectiveness of speed limit reductions and road design interventions on the number and severity of accidents, as well as their influence on driving behaviour in general. As previously discussed, these measures can significantly improve road safety and can partially explain the behaviour of drivers on certain road types and the choices they make regarding what speed to drive. The speed in which drivers choose to drive on certain roads and whether or not they comply with the speed limit can be further explained by the credibility of the speed limit in question. In order to understand and measure speed limit credibility, it is important to know the factors that influence credibility and the relationship between these factors. Relatively few studies have attempted to define and identify these factors and the relationships between them, and some have sought to come up with an objective tool to measure speed limit credibility. In this section, these factors will be explored and a conceptual framework will be presented that visualises the relationships between these factors, thereby contributing to the answering of the first research sub-question.

Before understanding the underlying factors that influence speed limit credibility, it is important to first define what credibility is, and what constitutes a credible speed limit. There is no single definition of what credibility is, as credibility can be quite subjective and dependent on individual perceptions. Some studies use slightly different definitions of credibility, but the most commonly used definition is the one defined by SWOV, in which they define credible speed limits as "limits that meet the expectations raised by the road and the road environment, so that drivers are more inclined to comply with them" (SWOV, 2021). From this definition alone, it can be seen that the road environment itself and its characteristics are a major factor in determining the credibility of a speed limit, which in turn is a factor that influences speed limit compliance. The relationship between road characteristics, speed limit credibility and speed limit compliance have been corroborated by multiple studies that investigated the subject of credible speed limits. One such study, conducted by Ambros et al. (2021), investigated the relationships between so-called "speed indicators", namely the official speed limit, perceived speed limit and the preferred speed chosen by drivers. In addition, they wanted to determine which road and personality characteristics influence these various speed indicators, particularly on the perceived speed limit and the preferred speed. In theory, the differences between these speed indicators should give an indication as to whether or not a speed limit is considered credible, however the authors ultimately could not draw any definitive conclusions that ties the differences in speed indicators to the credibility of a speed limit, and instead hypothesised that the perceived speed limit would best describe how credible a speed limit is (Ambros et al., 2021). Nevertheless, links can be made between the indicators that shows their influence on one another. Figure 3.1 shows a conceptual framework linking the indicators together.

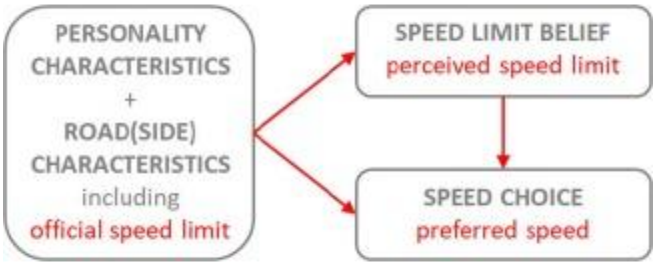

Figure 3.1. Relationships between speed indicators (Ambros et al., 2021).

The different speed indicators can be associated with the more general factors relating to road environment, speed limit compliance and speed limit credibility. As seen in Figure 1, the drivers' choice of speed is largely influenced by their belief of what the speed limit is on a given road, regardless of what the actual speed limit is. In this case, the mismatch between speed choice and the official speed limit can be used as a determinant of speed limit compliance (i.e., the bigger the mismatch between speed choice and the official speed limit, the less compliant drivers are with the speed limit, and vice versa). As mentioned previously, the authors believe that the perceived speed limit of drivers would provide a good indication as to whether or not a speed limit is considered to be credible, therefore the same could be said about the mismatch between the perceived speed limit and the official speed limit as a way to determine speed limit credibility (i.e., the bigger the mismatch, the less credible a speed limit is, and vice versa). Both speed limit belief and speed choice are influenced by personality and road(side) characteristics, with some characteristics having a more significant influence than others, such as road width and the presence of additional roadside elements like buildings and trees (Ambros et al., 2021). Similar relationships between road characteristics, speed choice and speed limit belief have been found by a study conducted by Charlton and Starkey (2017), in which they determined that speed choices correspond to expectations arising from the appearance of a road, and that speed limits that do not match these expectations were deemed to be not credible. In other words, the mismatch between the perceived speed limit and the actual speed limit gives a sense as to how credible, or not credible, a speed limit is for a given road, therefore justifying the findings of Ambros et al. (2021).

Several studies conducted by Yao et al. (2019a; 2019b; 2020a; 2020b) also investigated the relationships between road characteristics, speed limit compliance and speed limit credibility, but unlike the studies discussed previously, Yao et al. also examined the influence of drivers' risk perception on compliance and credibility, as well as how the road environment influences risk perception. The scope and the methodology employed in these studies are all similar in nature, as they all involved a mix of a driving simulator experiment and a questionnaire that asked respondents to rate the credibility of a given speed limit and their risk perception for each of the eight scenarios developed in the driving simulator. These scenarios depicted rural roads with varying characteristics, such as geometry, presence of a hard shoulder and the presence of bike lanes. A conceptual framework was developed that shows the relationships between the road environment, risk perception, speed limit credibility and speed limit compliance, seen in Figure 3.2.

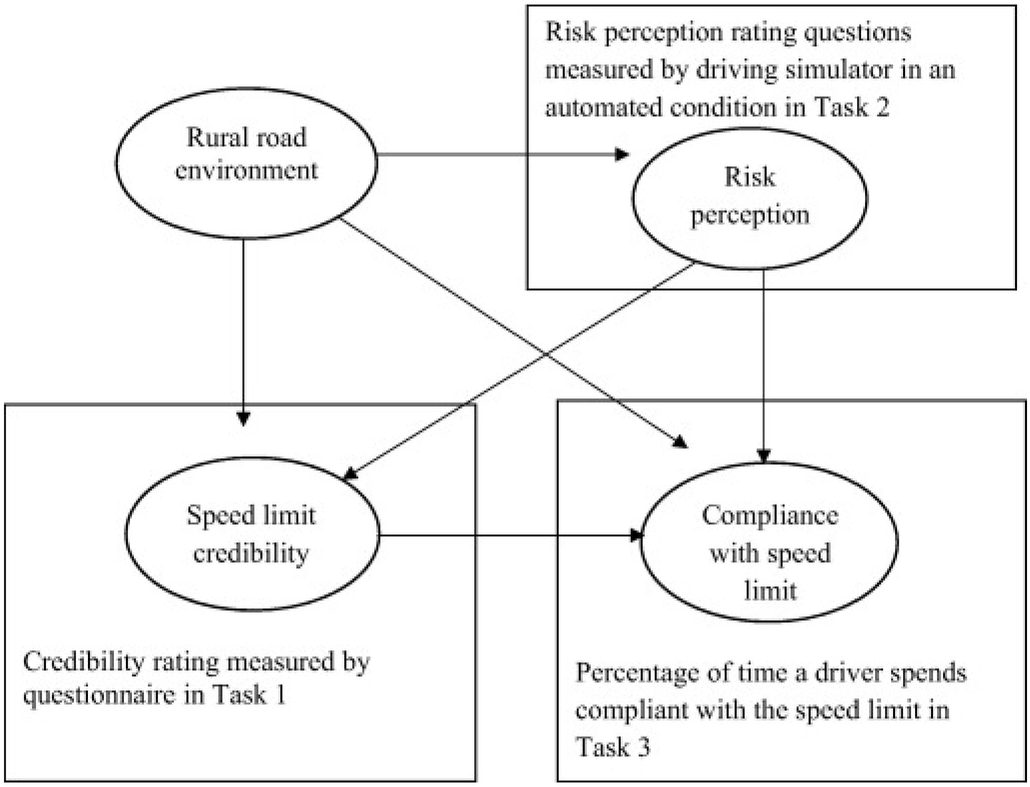

Figure 3.2. Relationships between road environment, risk perception, credibility and compliance (Yao et al., 2019a).

The framework developed by Yao et al. (2019a) confirms the relationships established by Ambros et al. (2021) and Charlton and Starkey (2017) with regards to the road environment, speed limit credibility and speed limit compliance. The added factor of risk perception provides a deeper understanding as to why drivers choose to drive at certain speeds and how they perceive speed limits. The drivers' choice of speed (a determinant of speed limit compliance) is ultimately influenced by their perceived credibility of a speed limit as well as their perception of risk when driving at a certain speed, which in turn are both influenced by objective factors such as road characteristics and subjective factors such as personality traits (Yao et al., 2020b). When drivers perceive the feeling of risk to be greater while driving on a road at a given speed, this may indicate that the speed limit set for that particular road may be too high and thus less credible (Yao et al., 2019a). This means that the relationship between speed limit credibility and risk perception are negatively correlated. As drivers feel more risk, they are more likely to reduce their speed and comply with the speed limit, indicating a positive relationship between risk perception and speed limit compliance. This is further reinforced by the credibility of a speed limit: The more credible a speed limit is, the more compliant drivers are with the speed limit, showing a positive relationship between speed limit credibility and speed limit compliance (Ambros et al., 2021; Charlton and Starkey, 2017; Yao et al., 2019a; 2019b; 2020a; 2020b).

From the literature, it is clear that there are significant relationships between the road environment, risk perception, speed limit compliance and speed limit credibility. A comprehensive conceptual model has been developed that expanded on previous conceptual models from the literature discussed to include factors that were also found to have an impact on speed limit credibility but were not discussed in detail, including institutional factors such as law enforcement and road policy, and societal factors such as demographics and social norms, shown in Figure 3.3.

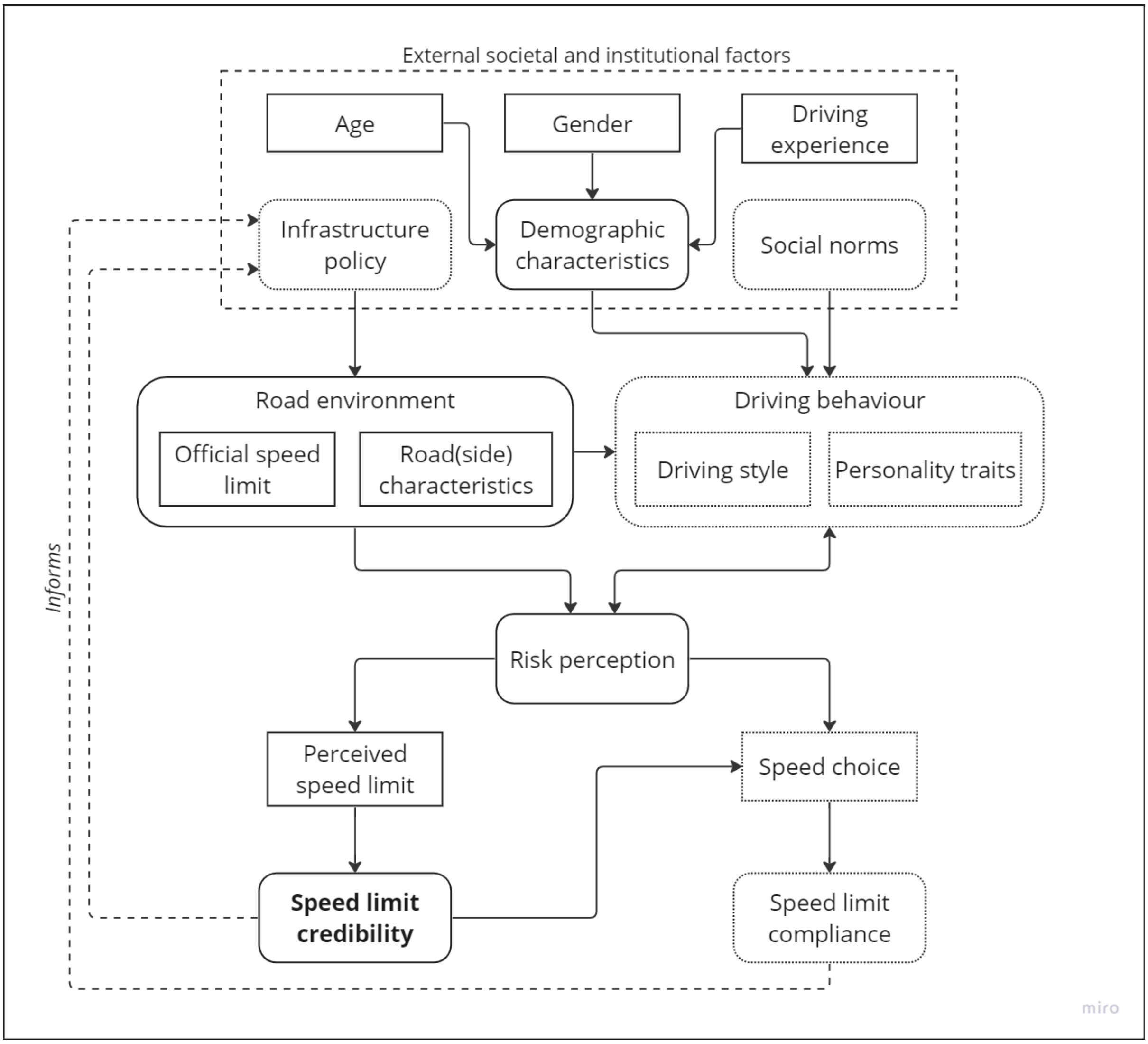

Figure 3.3. Conceptual model showing factors influencing speed limit credibility.

The conceptual model shows that two main factors ultimately influence speed limit credibility: The road environment (including the official speed limit and road(side) characteristics), and driving behaviour (determined by individual driving styles and personality traits). Both of these factors are externally influenced by various societal and institutional factors, such as infrastructure policy (which determines official speed limits and provides guidance on road design according to the road's intended function), demographic characteristics (which includes age, gender and driving experience, and therefore has a partial influence on driving behaviour), and social norms (influences driving behaviour to a large extent). Since speed limit credibility can be measured both objectively and subjectively, the road environment factor represents the objective (or tangible) aspect of speed limit credibility (through the measurement of vehicle speeds), while driving behaviour represents the subjective (or intangible) aspect (through the measurement of people's perceptions). In addition, driving behaviour can also be influenced by the road environment, such that drivers can adapt their behaviour according to how the road is designed. This relationship tends to be an indirect one, however, as the road environment directly influences how drivers perceive risk (e.g. increased complexity in road design may result in higher risk perception), and that perception of risk ultimately determines how drivers behave on the road (e.g. higher perception of risk results in more cautious driving). Not only does risk perception affect driving behaviour, but the way drivers perceive risk can also be influenced by their personality traits and their style of driving, resulting in a two-directional (or reinforcing) relationship between driving behaviour and risk perception (e.g. more anxious drivers are more sensitive to risk while more aggressive drivers are less sensitive).

As the road environment and driving behaviour do not directly influence speed limit credibility, an indirect relationship exists through risk perception as a common factor between them. Risk perception is influenced by both the road environment and driving behaviour, which in turn influences how drivers perceive the speed limit and how fast they choose to drive (speed choice). If the road environment results in a higher perception of risk among drivers, drivers may choose to lower their speed and perceive the speed limit for that road to be lower (assuming that they don't know what the actual speed limit is). Conversely, if the road environment results in a lower perception of risk, drivers may choose to driver faster and perceive a higher speed limit for that road. This perception of what drivers think the speed limit is on a particular road ultimately determines the credibility of the road's actual speed limit. If the perceived speed limit is aligned with the actual speed limit, then the speed limit is considered to be credible and appropriate for the road's design. If there's a misalignment between the perceived speed limit and the actual speed limit, then the speed limit is not considered to be credible and therefore inappropriate for the road's design.

Aside from being directly influenced by risk perception, speed choice is also partially influenced by speed limit credibility. In most cases, drivers tend to drive at speeds that match a given speed limit. If a speed limit is considered to be credible, then drivers are more likely to drive according to the speed limit, and therefore improving speed limit compliance. If a speed limit is not considered to be credible, then drivers are less likely to comply with the speed limit. Both speed limit credibility and the level of compliance ultimately informs road authorities on whether or not changes should be made to infrastructure policy that governs speed limits and road design, creating a feedback loop between policy and speed limit credibility/compliance. If speed limits are found to be not credible on certain roads, and/or if there is a high percentage of drivers that do not comply with the speed limit, then the road authorities can make targeted adjustments to infrastructure policies that would either change the speed limit to match the road's design or redesign the road altogether to make the speed limit more credible (i.e. change the road environment to improve speed limit credibility and compliance).

The scope of this thesis only covers factors that are outlined with a solid line in the conceptual model (demographic characteristics, road environment, risk perception and speed limit credibility). Factors that are outlined with a dotted line (infrastructure policy, social norms, driving behaviour and speed limit compliance) are not covered (in detail).

4. Results

In this chapter, the results of the analysis for sub-questions 2 and 3 are presented. The results will be divided into two sub-chapters: Firstly, the results of the analysis of actual vehicle speeds driven on selected road segments are discussed (sub-question 2), and then subsequently the results of the online survey and the analysis of speed limit credibility perceptions are presented (sub-question 3). Each sub-chapter is further divided into smaller sub-sections, with each sub-section discussing the results of a specific aspect of the analysis of their respective sub-questions, such as descriptive results of the road characteristics of the examined road segments for sub-question 2, descriptive results of the respondent characteristics from the survey for sub-question 3, and the results of the inferential statistical tests performed for each sub-question. The chapter will conclude with the main findings from each sub-chapter, with the aim of closing the research gap provided by sub-questions 2 and 3.

4.1. Analysis of road characteristic effects on vehicle speeds

This sub-chapter will focus primarily on the results of the analysis of sub-question 2, which is to understand the effects of specific road characteristics on actual driving speeds. The analysis aims to provide a clearer understanding of the impacts of individual road characteristics and of different road characteristic combinations in contemporary (Dutch) road design on chosen driving speeds, and how manipulating these characteristics can effectively reduce speeds in order to make GOW30 more credible. The results of the analysis may therefore provide an objective benchmark for policy makers and road authorities to assess the real-world effectiveness of (a combination of) certain road characteristics on bolstering the credibility of a 30 km/h speed limit in urban areas.

The results in this sub-chapter will be presented as follows: First, a comparative descriptive analysis of the selected road segments is discussed, which would allow a better understanding of the variation in speed limits and road characteristics between the chosen segments. Then, the descriptive results of the V85 (85th percentile) speed distributions per speed limit category will be shown. Finally, the results of the statistical tests (t-tests, ANOVA, linear regression, etc.) will be discussed which would ultimately determine whether or not certain road characteristics have significant effects on vehicle speeds, and to what extent these effects differ from other road characteristics.

4.1.1. Descriptive results of road segment characteristics

As described in the Methodology section, a total of 30 different road segments throughout the Netherlands were analysed for the purpose of this analysis. The road segments were chosen based on available data in the Telraam database, which includes data on traffic counts per mode and V85 speeds for each observation. The characteristics of each road segment were manually entered through visual inspection of the selected road segments. Traffic count and V85 speed data were recorded over a period of five days, between the 1st of July and the 5th of July 2024 (Monday to Friday, representing typical weekday traffic conditions). Furthermore, data was recorded over a four-hour period for each day, between the hours of 7 AM and 11 AM. The data was measured in hourly intervals, resulting in four separate observations of traffic counts and V85 speeds per day (V85 speeds were taken as an average speed measurement during the hour in which individual vehicle speeds were recorded). This amounted to 20 count and speed observations per road segment, and 600 observations in total (see Appendix D for descriptive tables of each road characteristic).

Of the 600 total observations, 420 (70%) of them were from 30 km/h roads (21 road segments), and 180 (30%) of them were from 50 km/h roads (9 road segments), as shown in Figure 4.1. There are no road segments that have a speed limit higher than 50 km/h as they are not considered to be relevant for the purpose of this analysis.

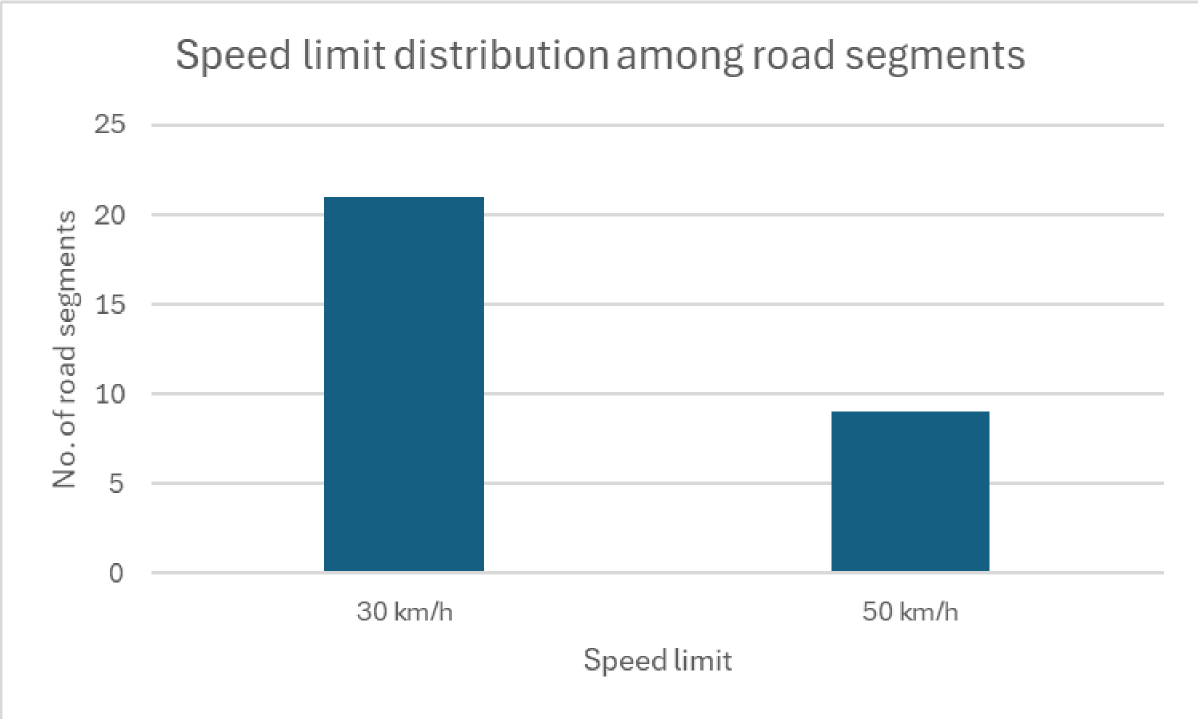

Figure 4.1. Observation frequency per speed limit category.

The road characteristics considered in this analysis include the number of lanes, the presence of a one-way street, lane width, the presence of lane markings, the type of road surface, the presence of bike lanes and their degree of separation from the main carriageway, and the presence of on-street parking. These characteristics were chosen based on existing literature and evidence of their known effects on vehicle speeds, as well as their relevance to the subject of speed limit credibility. Out of the 600 total observations, 580 (96.7%) of them were from roads with only one lane (per direction), while 20 (3.3%) of them were from roads with two lanes (per direction), as shown in Figure 4.2. This means that 29 of the 30 road segments analysed are either one-way streets with one lane or bi-directional roads with one lane in each direction, and only one road segment is a one-way street with two lanes (namely, Utrechtseweg).

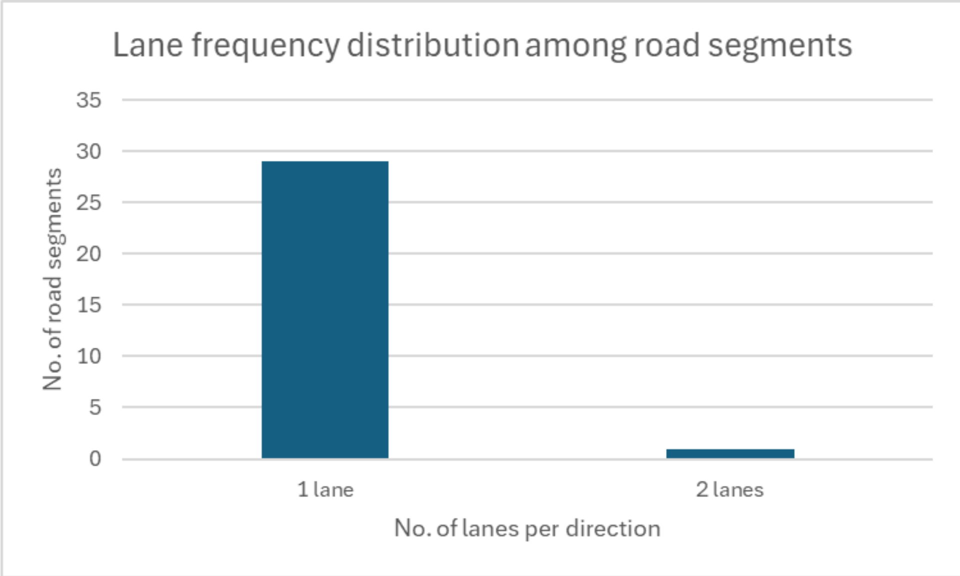

Figure 4.2. Observation frequency per lane category.

Because most urban roads in the Netherlands have either one or two lanes per direction, it is rare to find roads that have three or more lanes as they are usually only reserved for motorways. Even so, and as was made evident by the result, the prevalence of two-lane roads is slowly diminishing, due to updated road design guidelines and road safety standards that advises against the construction of new two-lane roads in urban areas, as well as advocating for the conversion of existing two-lane roads into one-lane roads. As a result of the lack of observations from road segments with two lanes or more, the number of lanes as a road characteristic will not be further examined in this analysis, as it will be difficult to draw definitive conclusions on its effects on vehicle speeds.

One-way streets account for 220 (36.7%) of the total observations, while the remaining 380 observations (63.3%) are on bi-directional roads, as shown in Figure 4.3. This translates to 11 one-way road segments and 19 bi-directional road segments. Out of the 220 one-way street observations, 180 of them are on 30 km/h roads (9 road segments) while the remaining 40 are on 50 km/h roads (2 road segments). Conversely, 240 out of the 380 bi-directional road segment observations are on 30 km/h roads (12 road segments) while the remaining 140 observations are on 50 km/h roads (7 road segments). The differences in observation frequencies between one-way streets and bi-directional roads categorised by speed limit is shown in Figure 4.4.

Figure 4.3. Observation frequency per street classification (one-way or bi-directional).

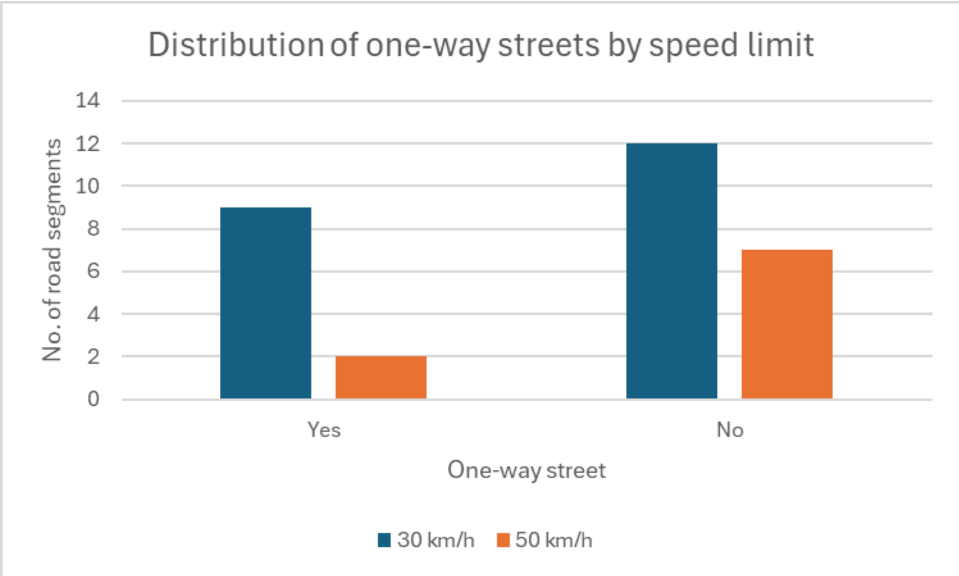

Figure 4.4. Observation frequency per street classification (one-way or bi-directional) categorised by speed limit.

Based on the results, it can be seen that the proportion of one-way streets relative to bi-directional roads is much higher for 30 km/h roads than it is for 50 km/h roads, even though in both cases there are more bi-directional roads than there are one-way streets. This finding is in line with current understanding of how one-way streets are implemented, as they are more commonly found on 30 km/h roads than on 50 km/h roads. As such, this indicates that a relationship exists between speed limit classification and one-way street implementation, which may prove to be a confounding variable further down in the analysis and result in problems relating to multicollinearity when determining the stand-alone effects of this particular road characteristic on vehicle speeds.

For the purposes of this analysis, lane markings (or longitudinal markings) are defined as markings on the road surface that separate driving lanes from one another. These markings can either be broken (dashed) lines or solid (continuous) lines. In the case of bi-directional roads with one lane in each direction, the presence of lane markings represents the division of traffic flowing in opposite directions, and in the case of roads with multiple lanes in each direction, lane markings represent the division of traffic flowing in the same direction (typically demarcated by dashed lines) and, if it's a bi-directional road, the division of traffic flowing in opposite directions (typically demarcated by single or double solid lines). Lane markings are almost never applied to one-way streets with only one lane as it would not serve any real purpose.

Out of the 600 total observations, 120 (20%) of them are from road segments that do have lane markings present, while the remaining 480 observations (80%) are from road segments that do not have lane markings present, as shown in Figure 4.5. This translates to 6 road segments and 24 road segments, respectively. Furthermore, the majority of observations on road segments without any lane markings present come from 30 km/h roads (400 out of 480 observations, equivalent to 20 road segments), while the majority of observations on road segments with lane markings present come from 50 km/h roads (100 out of 120 observations, equivalent to 5 road segments). These differences are graphically displayed in Figure 4.6.

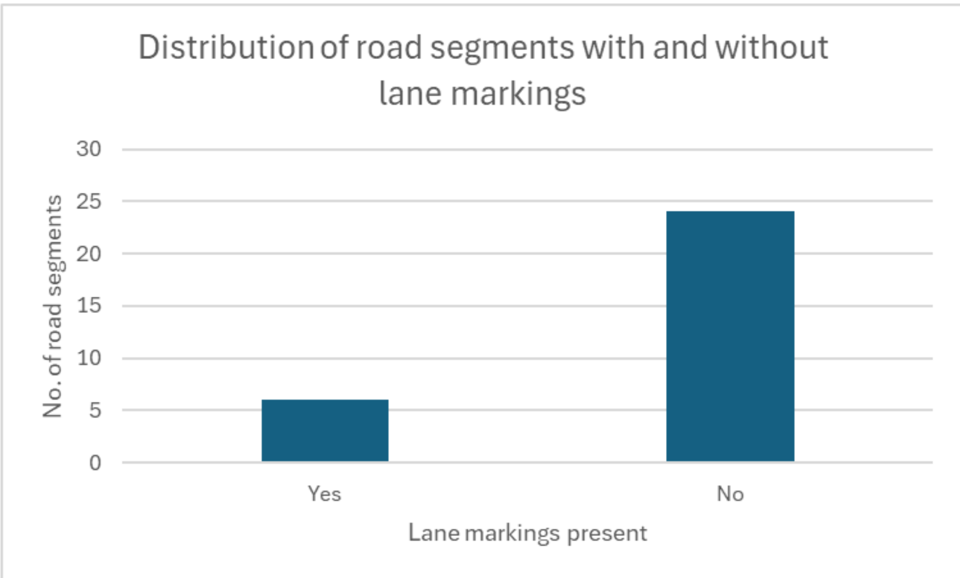

Figure 4.5. Observation frequency of lane marking characteristics.

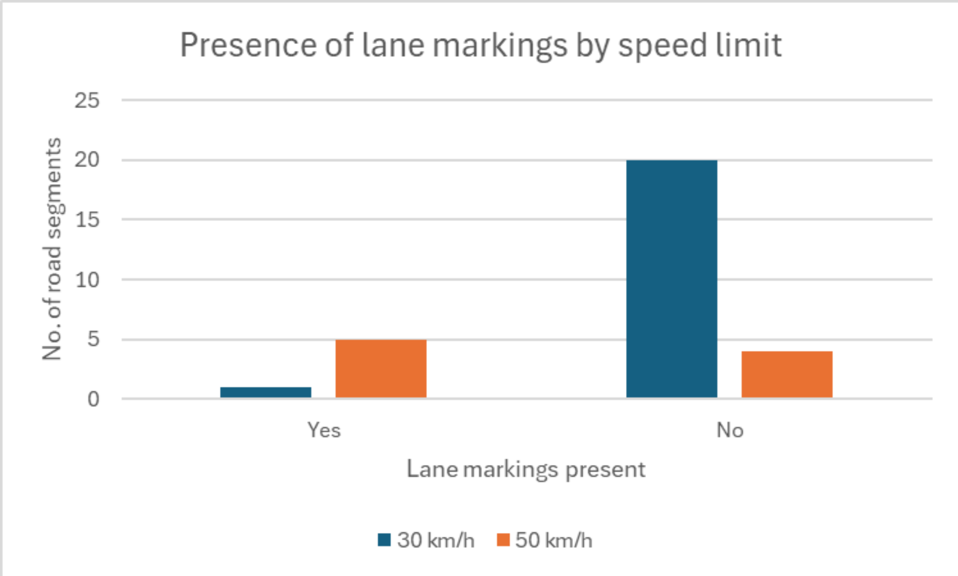

Figure 4.6. Observation frequency of lane marking characteristics categorised by speed limit.

These findings are in line with expectations of how and when lane markings are implemented, as current road design guidelines do not incorporate the use of lane markings in the design of most 30 km/h roads, and as such are usually reserved for the design of 50 km/h roads. As is the case with one-way streets, the relationship between the use of lane markings and speed limit classification may result in a potentially confounding variable as the issue of multicollinearity may arise when analysing the individual effects of lane markings on vehicle speeds.

The surface of a road is a road characteristic that is determined by the type of material that was used to pave the road. This includes colour differences between road surfaces that are made from the same material. From the 30 road segments analysed, three types of road surfaces were found, namely brick, dyed asphalt and grey asphalt. The difference between dyed and grey asphalt is, as implied in their names, the colour of the asphalt, in which a pink dye is used to give the colour of dyed asphalt, while grey asphalt is the conventional type of asphalt that is used for the vast majority of asphalt-paved roads. Dyed asphalt is typically only used for roads that are classified as “bike streets” (i.e. roads which allow motor vehicle access, but cyclists have priority), as it is same type of dye used for bike paths and would therefore give drivers the sense that they are driving on a street with cyclist priority.

The frequency of observations on roads that are paved with either brick or grey asphalt are even at 280 observations each (46.7% of total observations), which is equivalent to 14 road segments per road surface type. Dyed asphalt accounts for the remaining 40 observations (6.7% of the total), equivalent to just 2 road segments. These frequencies and percentages are shown in Figure 4.7.

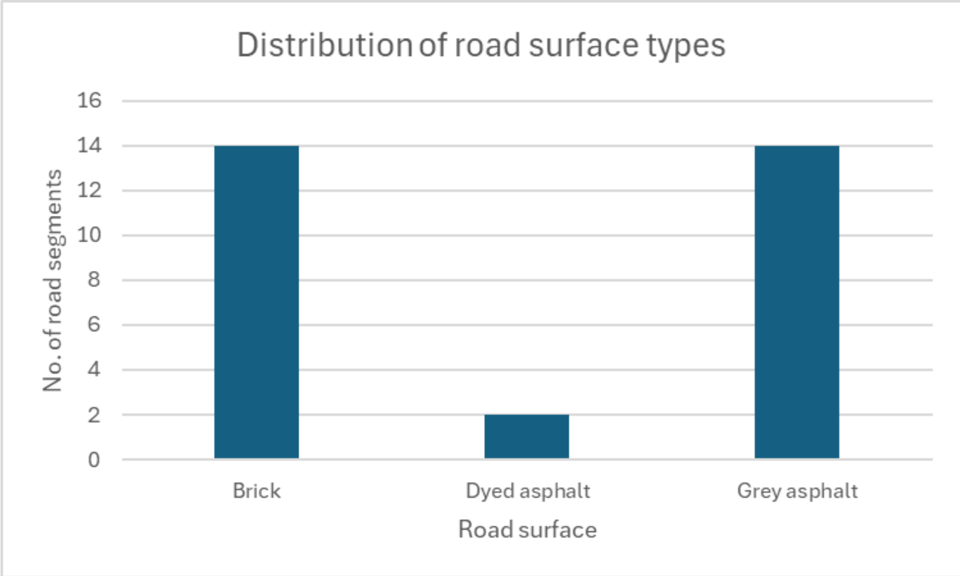

Figure 4.7. Observation frequency of road surface characteristics.

When examining the distribution of road surface characteristics based on speed limit classification, it was found that the majority of brick-paved roads are 30 km/h roads (240 out of 280 observations), while only 2 road segments are brick roads with a 50 km/h speed limit. The distribution of roads paved with grey asphalt are evenly split between both 30 km/h and 50 km/h roads (140 observations each). As expected, the two road segments paved with dyed asphalt are only found to have a 30 km/h speed limit, representing the two “bike streets” in the sample of road segments. These distributions are shown in Figure 4.8.

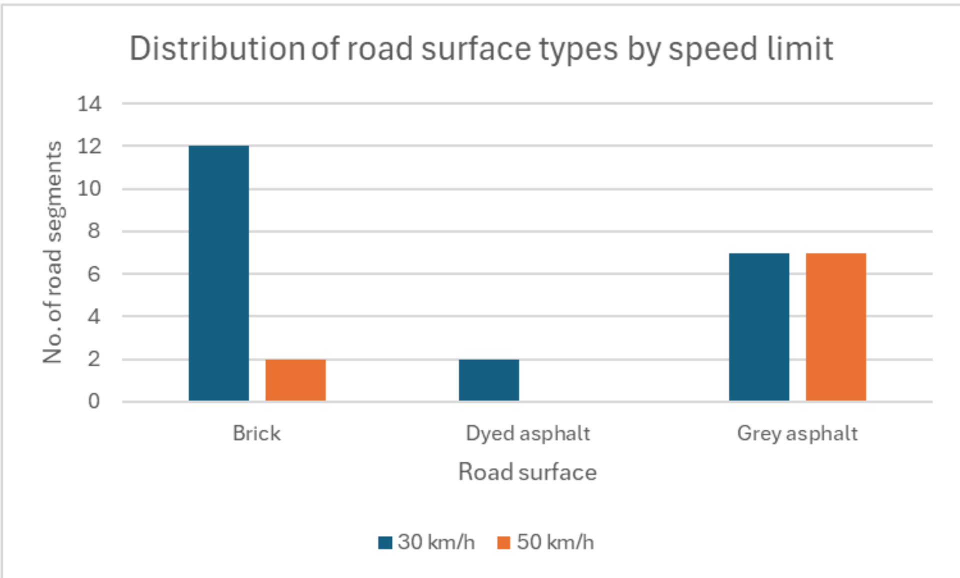

Figure 4.8. Observation frequency of road surface characteristics categorised by speed limit.

A particularly important road characteristic, especially in the context of Dutch road design, is the presence of bicycle lanes. They are prevalent throughout the Netherlands and are an integral part of

Dutch road design. The way in which they are integrated into the design of a road can vary depending on the road's classification and function. In general, three main categories of bike lanes can be distinguished: Bike lanes that are completely separated from the main road (divided by a buffer), bike lanes that are integrated into the main road but have their own right-of-way along the road's edge (also known as a bicycle gutter), and roads without any bike lanes present (cars and bikes share the same space). These three categories were observed in the analysis of the selected road segments. However, two additional categories were also found: Bi-directional road segments with a bicycle gutter in one direction and an absent bike lane in the other direction (mix gutter/none), and bi-directional road segments with a bicycle gutter in one direction and a separated bike path in the other direction (mix gutter/separated).

Road segments with bicycle gutters present account for the highest frequency of observations out of all the bike lane categories (300 out of 600 observations, equivalent to 15 road segments). Road segments without any bike lanes present account for 200 observations (10 road segments). Roads that have separated bike paths as well as roads that have a mix of a separated bike path and a bicycle gutter account for 40 observations each (2 road segments per category). Finally, there is only one road segment that has a mix of a bicycle gutter and an absent bike lane. Figure 4.9 shows these observation frequencies per category.

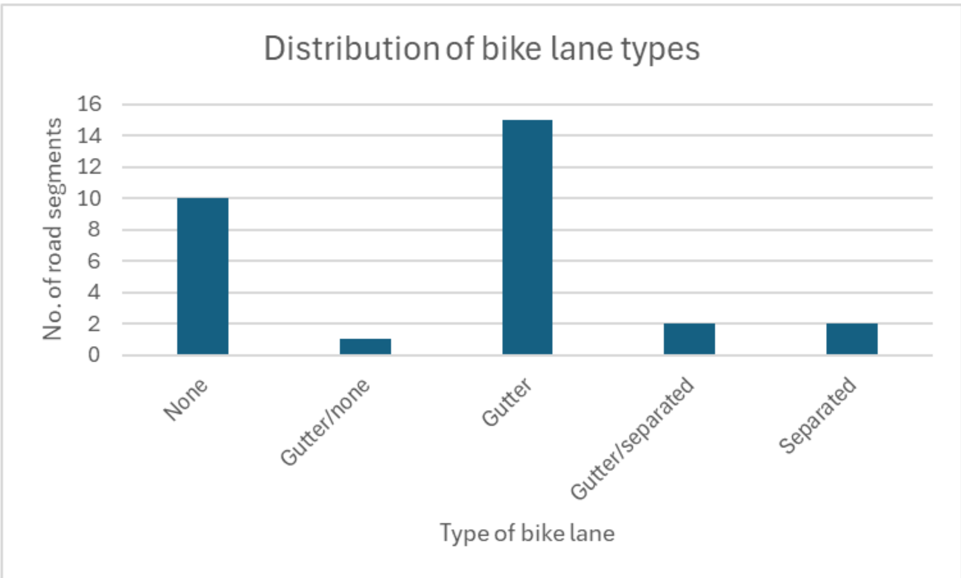

Figure 4.9. Observation frequency of bike lane characteristics.

In terms of the distribution of bike lane characteristics by speed limit category, all road segments that do not have any bike lanes present are 30 km/h roads, while the only two road segments that have separated bike paths are both 50 km/h roads. This is an expected finding since a 30 km/h speed limit is safe enough for cyclists that bike lanes are not strictly necessary for those roads, while roads that have a 50 km/h speed limit do require some degree of separation between cyclists and motor traffic due to their relatively unsafe speeds. The distribution of road segments that have bicycle gutters present are almost evenly split between 30 km/h roads and 50 km/h roads, with 160 observations on 30 km/h roads (13 road segments) and 140 observations on 50 km/h roads (12 road segments). The two categories that have mixed characteristics are both only found on 30 km/h roads. These distributions are shown in Figure 4.10.

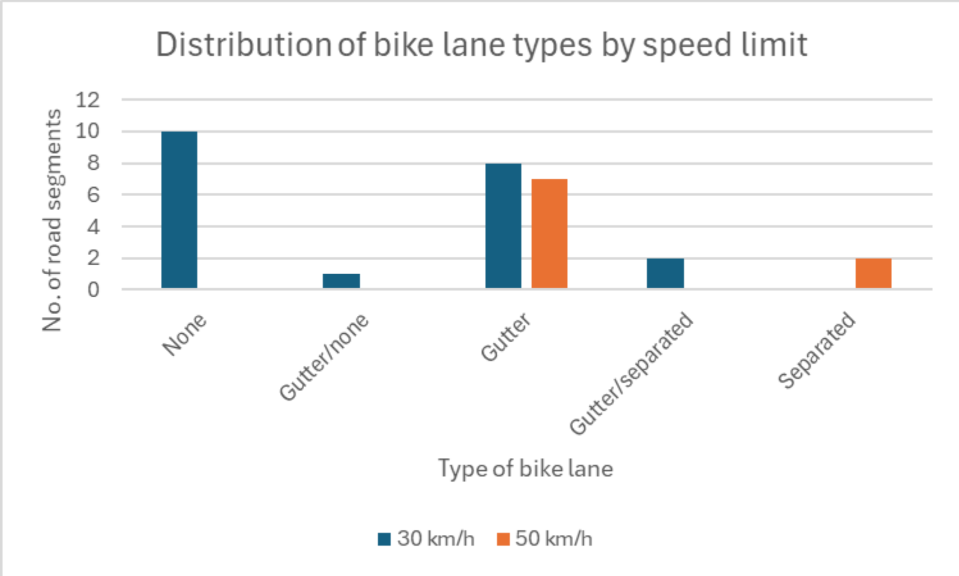

Figure 4.10. Observation frequency of bike lane characteristics categorised by speed limit.

The presence of on-street parking is another potentially important road characteristic that may affect vehicle speeds. On-street parking in this case refers to the existence of parking provisions on the side of the road. This can either come in the form of parking on the curb or dedicated parking spaces on the road's offset. From the analysis of the road segments, it has been found that the majority of road segments do have some form of on-street parking (80% of total observations, equivalent to 24 road segments). The remaining 20% (6 road segments) do not have any on-street parking provided. These results are shown in Figure 4.11.

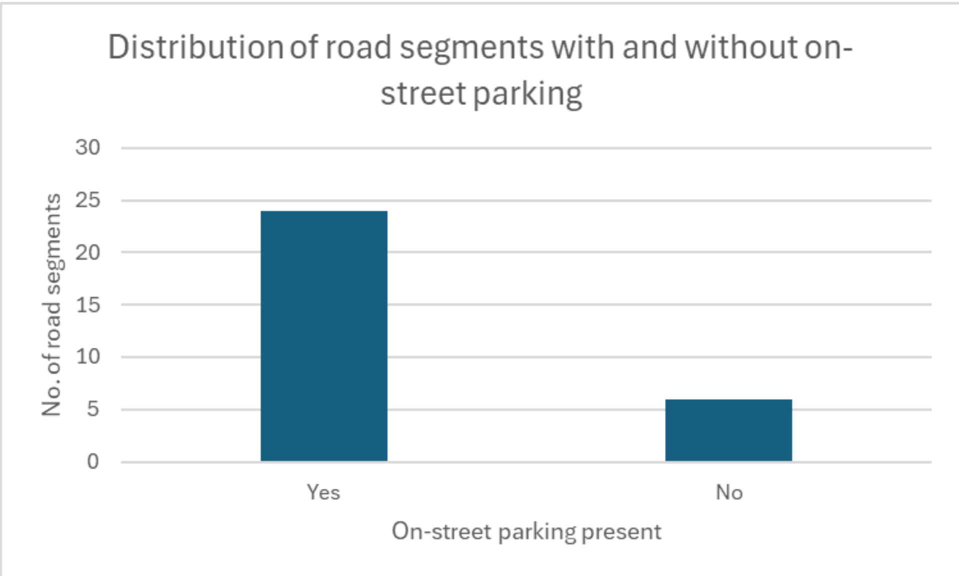

Figure 4.11. Observation frequency of on-street parking characteristics.

The majority of road segments with on-street parking are 30 km/h roads, while most of the very few road segments without on-street parking are 50 km/h roads. The disparity in observations between road segments with on-street parking and road segments without on-street parking on 30 km/h roads is relatively large compared to 50 km/h roads, in which the number of 50 km/h road segments with and without on-street parking are almost equal. However, it is worth noting that the number of observed 50 km/h road segments with on-street parking is slightly higher than those without on-street parking (5 road segments and 4 road segments, respectively), implying that on-street parking is a generally common characteristic among urban roads. Figure 4.12 shows the distribution of on-street parking characteristics by speed limit.

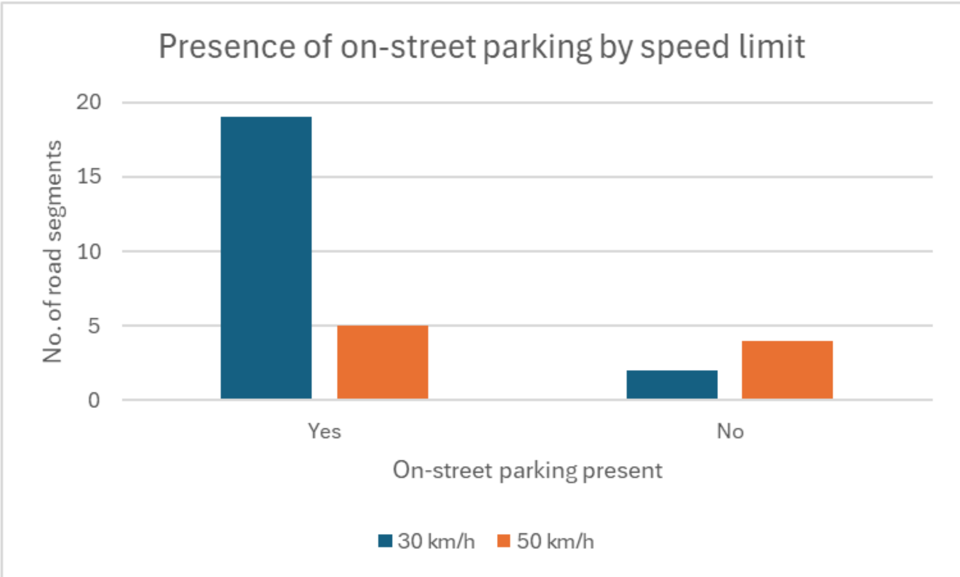

Figure 4.12. Observation frequency of on-street parking characteristics categorised by speed limit.

The last road characteristic that was selected to be examined in this analysis is lane width. The definition of lane width is fairly straightforward and self-explanatory, but the ways in which lane width is measured may vary depending on how a road is laid out. For most bi-directional roads with one lane in each direction, lane width is measured as the distance between the centreline marking and the curb (or edge line markings in some cases). If on-street parking is present, then the width of a lane is measured between the centreline and the edge of the parking provision, therefore the parking provision itself is not included in lane width measurements. For roads with multiple lanes per direction, lane width is measured as the distance between lane markings, and for one-way streets, lane width is measured from curb to curb (or between the edges of parking provisions if on-street parking is present). Bicycle gutters are not included in lane width measurements.

The road segments analysed have lane widths that range from 1.50 metres to 5.25 metres. The lane width that was found to be the most common is 4 metres (one-third of all road segments), while a lane width of 2 metres is the second most common (23.3% of all road segments). The third most common lane width is 2.5 metres (13.3% of road segments), and the rest of the recorded lane widths are each found in only one or two road segments. Figure 4.13 shows the distribution of observation frequencies by lane width.

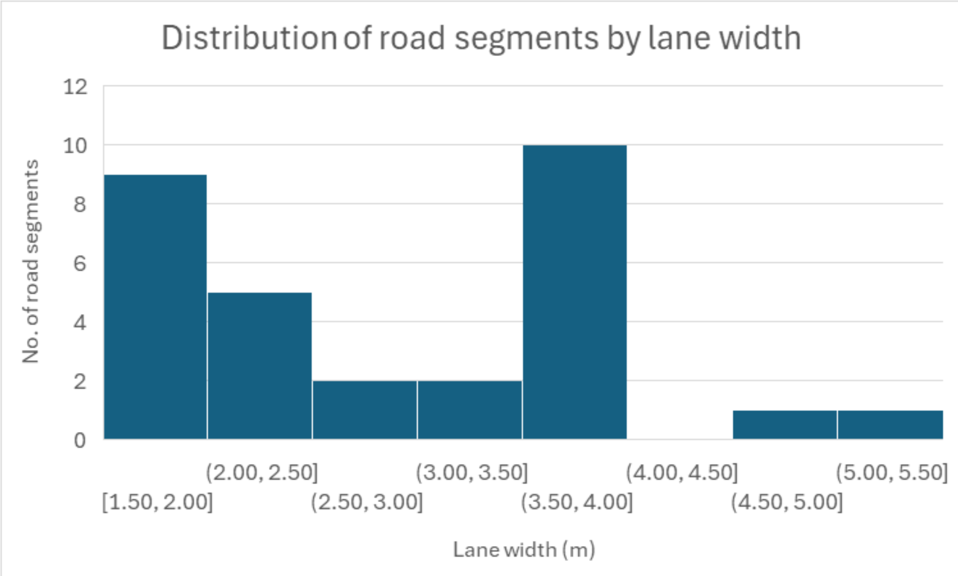

Figure 4.13. Frequency distribution of observed lane widths.

Lane widths of 30 km/h roads range from 1.5 metres to 5 metres, while the lane widths of 50 km/h roads range from 2 metres to 5.25 metres (see Appendix D, Figure D.1). 90% of road segments that have a lane width of 4 metres have a 30 km/h speed limit. Furthermore, 71.4% of road segments that have a lane width of 2 metres also have a 30 km/h speed limit. The most frequently observed lane width among 50 km/h roads is 2.5 metres, accounting for one-third of all 50 km/h road segments. A lane width of 2 metres accounts for the second most frequently observed among those roads.

It is further interesting to note that most of the one-way street segments have a 4-metre lane width, while all road segments with a 2-metre and a 2.5-metre lane width are bi-directional roads (Appendix D, Figure D.2). There is also a smaller range in lane widths among one-way streets compared to bi-directional roads, with lane widths ranging from 3 metres to 5 metres for one-way streets, and from 1.5 metres all the way to 5.25 metres for bi-directional roads. These findings imply that one-way streets tend to be wider than bi-directional road lanes, which may be due to the fact that the width of one-way streets are measured from curb to curb rather than between lane markings, as is the case with bi-directional roads.

4.1.2. Descriptive results of vehicle speeds

In order to assess the effects of various road characteristics on chosen driving speeds, it is important to first take a look at the general speed distributions on specific road categories. These speed distributions can be useful in providing a preliminary indication of the level of compliance towards a given speed limit, and in turn would provide an indication of the credibility of that speed limit. As mentioned in the introductory paragraph of the previous section, the 85th percentile (V85) speed is used as the primary parameter for average speed measurements. This measurement is taken as the speed at which 85 percent of vehicles travel at or below on a road segment at any given hour and is generally considered to be a representative indication of typical driving speeds under normal traffic conditions.

To ensure reliable and representative V85 speed measurements, a sufficient amount of motor vehicles would need to be observed. For this purpose, traffic counts are a useful measure to look at in determining this level of sufficiency. Traffic counts recorded by Telraam measure the counts of four different mode categories: Car, heavy vehicles (such as trucks and lorries), bike and pedestrian. Since this analysis is primarily concerned with the speeds of personal motor vehicles, only car traffic counts are looked at. In total, 122,108 cars were observed for all road segments combined, with a mean of 204 cars per observation. The observation with the highest car traffic count is 1037, while the lowest is 0. The relatively high sum of traffic counts and a reasonable mean count per observation indicates that a sufficient number of cars have been observed to ensure representative vehicle speeds among the population.

To understand what vehicle speeds are typically driven on urban roads, and to help gain insight into the level of speed limit compliance (a factor of speed limit credibility) among drivers towards urban speed limits (i.e. 30 km/h and 50 km/h speed limits), it is important to look at the speed distributions on roads with different speed limits. Figure 4.14 shows the V85 speed distribution on road segments with a 30 km/h speed limit.

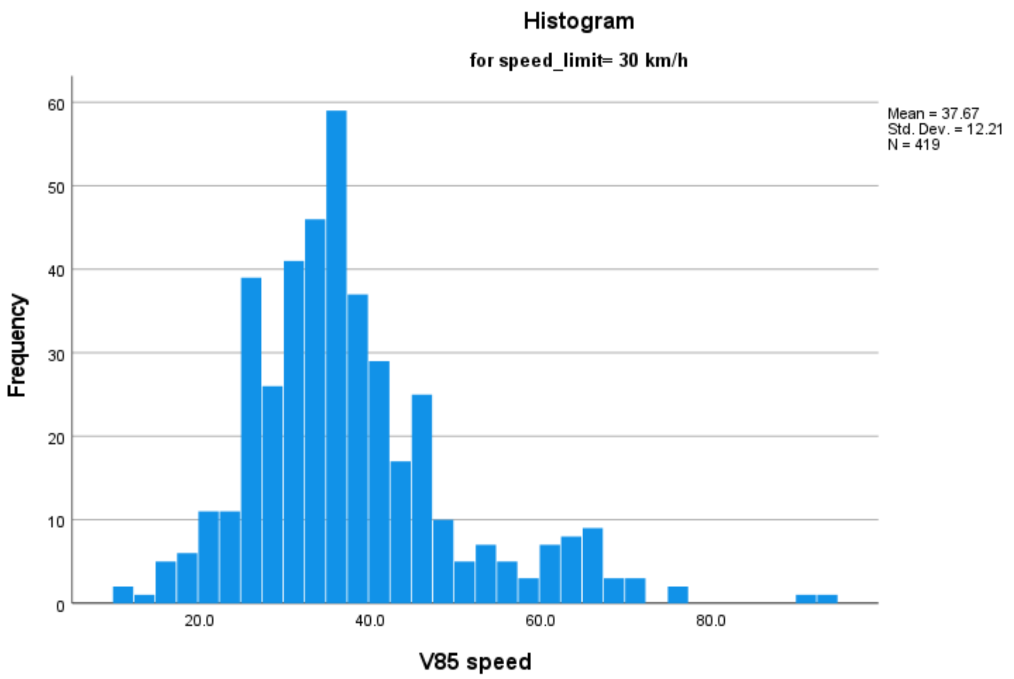

Figure 4.14. V85 speed distribution for 30 km/h roads.

There is a total of 419 recorded speed observations on 30 km/h road segments (there were initially 420 observations, however one observation has a missing value). The observed V85 speeds range from 11 km/h to 94 km/h, which indicates a large dispersion of vehicle speeds driven on 30 km/h roads. The maximum observed value of 94 km/h is intriguing, as it would imply that there was an instance where 85 percent of drivers were driving 64 km/h faster than the speed limit during a certain hour. Given the nature of how 30 km/h roads are designed and the surrounding environmental context in which they are most commonly implemented (i.e. residential areas), the 94 km/h observation seems unrealistic and would therefore be treated as a potential outlier, which will be further discussed later on.

Based on the current distribution, the mean V85 speed is found to be approximately 38 km/h, with a standard deviation of 12.21. The mean statistic could be interpreted such that, on average, 85 percent of drivers drive at or below a speed of 38 km/h on roads with a 30 km/h speed limit. The relatively high standard deviation shows that there are large variations in speeds driven on those roads. Due to the large variation in vehicle speeds, as well as the fact that the mean V85 speed is higher than the speed limit, this may indicate general issues with speed limit compliance among drivers, and would therefore have ramifications on speed limit credibility, particularly on 30 km/h roads.

As mentioned previously, there are some noticeable outliers in the distribution of V85 speeds, especially regarding the observed speed of 94 km/h. The other noticeable outlier in the distribution is measured to be 91 km/h, which is again an unrealistic measurement. There were several other observations which were inconsistent with the rest of the observations from the same road segments. For example, measurements of 76.5 km/h were found on road segments that had consistent measurements between 20 km/h and 40 km/h. These inconsistencies are considered to be faulty and are thus treated as outliers. The reason for these faulty readings could be due to poor weather conditions at the time of observation, as the accuracy of the readings may be significantly diminished as a result of bad weather. It is also worth noting that most of the inconsistent readings were taken on different road segments during the same day, further reinforcing the notion that a bad weather event took place on that particular day. Ultimately, seven outliers were identified and were subsequently removed from the dataset, resulting in a new distribution of V85 speeds on 30 km/h roads. This updated distribution is shown in Figure 4.15.

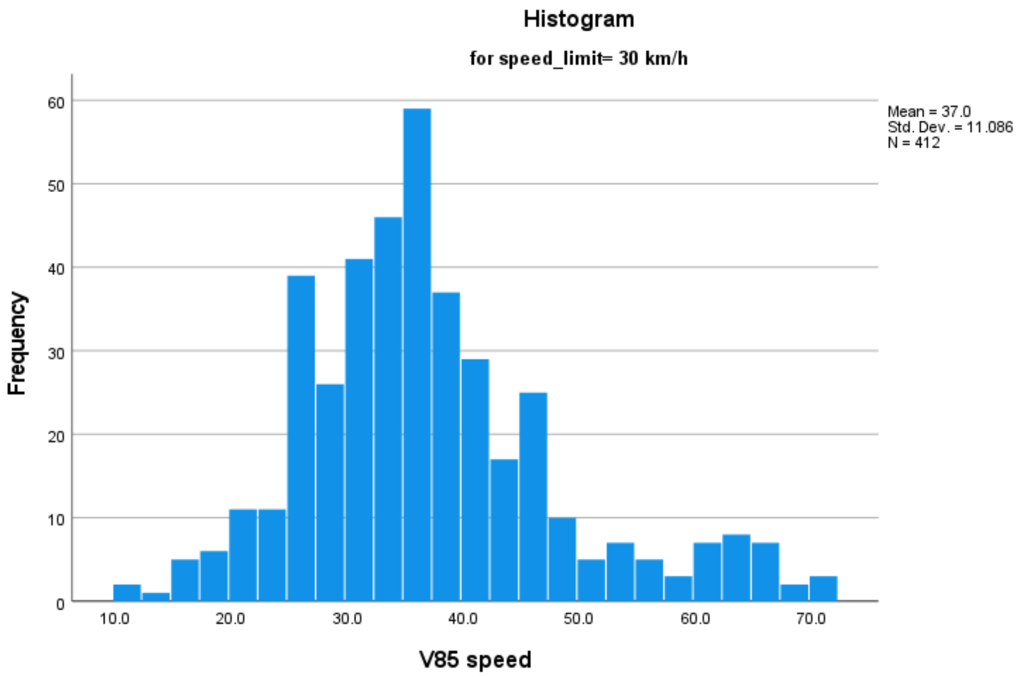

Figure 4.15. V85 speed distribution for 30 km/h roads without outliers.

As a result of the removal of outliers, there is now a total of 412 valid speed observations on 30 km/h road segments. The observations range from 11 km/h to 71.5 km/h, a significant decrease from the original distribution. Even with this decrease in range and the removal of outliers, the dispersion of vehicle speeds is still quite large, and the majority of speed observations is still found to be higher than 30 km/h. This is further reinforced by a mean V85 speed statistic of 37 km/h (a 1 km/h decrease from the original distribution), and a standard deviation of 11.086. As such, this is still an indication of a general non-compliance among drivers with regards to a 30 km/h speed limit, which in turn is an indication that a 30 km/h speed limit may not be credible for many of these roads.

Another interesting aspect of the distribution that is worth noting is that most of the V85 speed observations above 60 km/h belong to a single road segment, namely the Wittevrouwensingel in Utrecht. This particular road has a speed limit of 30 km/h, however through the analysis of vehicle speeds it has been found that most drivers consistently drive at speeds between 60 km/h and 70 km/h on this road, which is more than twice the speed limit. Due to the consistency of speed observations, the measurements are not considered to be faulty and are therefore not treated as outliers. The road segment itself may be considered as an outlier in relation to other road segments with the same speed limit, as it does not conform to the expected speed distribution for most 30 km/h roads, however it may provide useful information regarding the design of the road as a reason for the relatively high vehicle speeds. It is thus imperative to examine the specific characteristics of this particular road segment and how it compares to other road segments in influencing vehicle speeds.

As for the distribution of V85 speeds on road segments with a 50 km/h speed limit, there are some noticeable differences between this distribution and the speed distribution for 30 km/h road segments. As established previously, there is a significantly lower number of observations for road segments with a 50 km/h speed limit compared to those with a 30 km/h speed limit (180 V85 speed observations on 50 km/h roads). The V85 speeds range from 30.5 km/h to 74 km/h, indicating a smaller dispersion of speeds driven compared to that of 30 km/h roads. The mean V85 speed was found to be approximately 46 km/h, with a standard deviation of 9.038. The majority of speed observations were found to be lower than 50 km/h, meaning that drivers are generally compliant with a 50 km/h speed limit, and it further indicates that a 50 km/h speed limit is credible for most of these roads. The V85 speed distribution for 50 km/h road segments is shown in Figure 4.16.

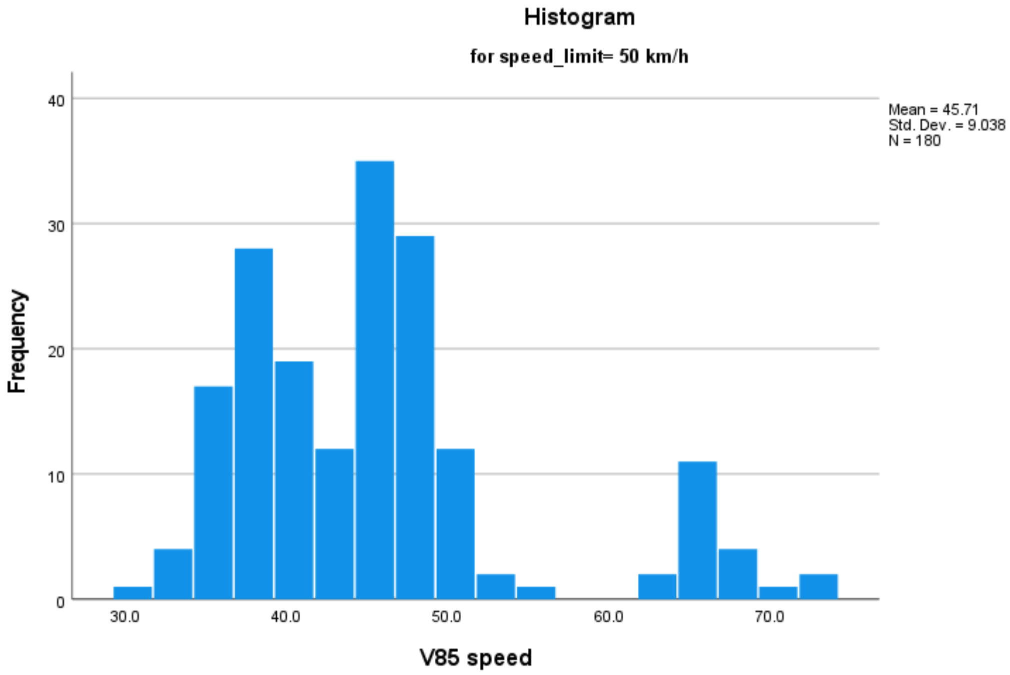

Figure 4.16. V85 speed distribution for 50 km/h roads.

It is important to note that no significant outliers were found in the distribution (i.e. no faulty or unrealistic measurements), unlike in the distribution for 30 km/h road segments. However, an obvious stand-out can be seen in which a separate, mini-distribution is observed for V85 speeds above 60 km/h. Similar to the case of the Wittevrouwensingel in the 30 km/h distribution, the mini-distribution observed in the 50 km/h distribution all belong to one road segment, namely the Geestersingel in Alkmaar. The V85 speeds on this road segment were consistently measured between 63 km/h and 74 km/h, and due to this consistency, the measurements are not regarded as faulty or unreliable. This, however, is still a significant deviation from the expected speed distribution and thus the relatively high vehicle speeds may ultimately be a consequence of road design. It would therefore be interesting to look at the specific characteristics of this particular road segment and how these characteristics would, in this case, decrease the credibility of a 50 km/h speed limit.

4.1.3. Individual road characteristic effects on vehicle speeds

The previous two sub-sections examined the descriptive characteristics of road segments and vehicle speeds, which contributes to a general understanding of the distribution of road characteristics among the examined road segments as well as the typical speeds being driven on 30km/h and 50 km/h roads. This sub-section explores the effects of individual road characteristics on vehicle speeds, and how these road characteristics may ultimately influence speed limit credibility. Each road characteristic will be examined to understand how vehicle speeds differ between road segments with varying categories of the same road characteristic, and whether or not these speed differences are statistically significant. A variety of statistical tests were utilised to determine the statistical significance of each road characteristic, in which the selected test depends on the number of categories and the nature of the variables of a given road characteristic. The road characteristics are tested independently by speed limit to ensure that any statistically significant result is not due to the difference in speed limit. All results in the form of SPSS output tables are displayed in Appendix E, which will be referenced to throughout this sub-section.

Since this sub-section primarily examines the individual effects of road characteristics on vehicle speeds, it is assumed that all other factors remain constant (i.e. other road characteristics do not have an effect on vehicle speeds). The combined effects of road characteristics are examined in the following sub-section.

Speed limit

The distribution of vehicle speeds discussed in the previous sub-section already gives an indication of the level of compliance among drivers towards 30 km/h and 50 km/h speed limits. It was implied that drivers, on average, are less compliant towards a 30 km/h speed limit, but are more compliant towards a 50 km/h speed limit. To test whether or not these indications are statistically significant, a couple of one-sample t-tests were conducted that compares the mean V85 speed against a hypothesised value (which in this case would be the speed limit in question). First, a one-sample t-test was conducted for speeds driven on 30 km/h roads (using 30 as a test value), and then a t-test was conducted for speeds driven on 50 km/h roads (using 50 as a test value). These tests will determine whether or not the mean V85 speeds are significantly different from their respective speed limits, and result in definitive conclusions regarding the degree of compliance among drivers towards those speed limits.

The null hypothesis for a one-sample t-test conducted on speeds driven on 30 km/h roads is stated as follows: *The mean V85 speed driven on roads with a 30 km/h speed limit is equal to 30 km/h*. The result of the test shows that the p-value is smaller than 0.001 (Appendix E, Table E.2), meaning that the result is statistically significant, and therefore the null hypothesis can be rejected based on the 95% confidence interval (and even on a 99% confidence interval). It can therefore be concluded that the mean V85 speed on 30 km/h roads is significantly different than the 30 km/h speed limit, and given that the mean speed is approximately 7 km/h higher than the speed limit (Appendix E, Table E.1), it can also be concluded that drivers in general do not comply with the 30 km/h speed limit, which would have further repercussions on the credibility of 30 km/h speed limits on most roads.

As for speeds driven on 50 km/h roads, the null hypothesis for this t-test is stated as follows: *The mean V85 speed driven on roads with a 50 km/h speed limit is equal to 50 km/h*. Just like the result of the t-test for 30 km/h roads, the result of this test shows that the p-value is smaller than 0.001 (Appendix E, Table E.4), meaning that this result is also statistically significant, and therefore the null hypothesis can also be rejected based on the 95% (and the 99%) confidence interval. It can therefore be concluded that the mean V85 speed on 50 km/h roads is significantly different than the 50 km/h speed limit. However, unlike the mean speed driven on 30 km/h roads, the mean speed driven on 50 km/h roads is lower than the speed limit (Appendix E, Table E.3), meaning that drivers are generally compliant towards a 50 km/h speed limit, and therefore making a 50 km/h speed limit credible for most of those roads. The question now is to what extent road characteristics play a role in making a 50 km/h speed limit more credible than a 30 km/h speed limit, and how these road characteristics can be manipulated to improve the credibility of 30 km/h speed limits?

One-way streets

The first road characteristic to be examined is the presence of one-way streets. To determine its effects on vehicle speeds, two-sample (or independent samples) t-tests were conducted separately for 30 km/h roads and 50 km/h roads. These tests compare the mean V85 speeds between the two categories of the "one-way street" variable ('yes', one-way street; or 'no', bi-directional road). The null hypothesis for these tests is that the mean V85 speed on one-way streets is equal to that of bi-directional roads. For both 30 km/h and 50 km/h roads, the tests result in p-values smaller than 0.001 (Appendix E, Tables E.6 and E.8, respectively; assuming that variances in V85 speeds between the two categories are equal). These results show that there is a significant difference in mean speeds between the two categories on both 30 km/h and 50 km/h roads, and in both cases, the null hypothesis is therefore rejected based on the 95% (and 99%) confidence interval. It can therefore be concluded that the presence of one-way streets has a significant effect on vehicle speeds, regardless of what the speed limit is. The only difference between the effects that one-way streets have on speeds driven on 30 km/h roads and 50 km/h roads is the direction of these effects. On 30 km/h roads, the mean speed is higher on one-way streets than on bi-directional roads (Appendix E, Table E.5), while on 50 km/h roads, the mean speed is higher on bi-directional roads than on one-way streets (Appendix E, Table E.7). This would imply that one-way streets may actually decrease the credibility of a 30 km/h speed limit and improve the credibility of a 50 km/h speed limit. Of course, the extent of these effects on speed limit credibility would ultimately depend on how one-way streets interact with other road characteristics, the most notable of which is lane width.

Lane width

According to theory and empirical evidence, the width of a road or a lane is arguable one of the biggest determinants of vehicle speed. Evidence suggests that the larger the width of the road or lane is, the higher the vehicle speeds are. To test if this is indeed the case in the context of this research, a simple linear regression was carried out that would determine if a relationship exists between lane width and vehicle speed. As with the analysis of other road characteristics, the regression was conducted separately for each speed limit category.

The regression results for speeds driven on 30 km/h roads shows that there is a significant correlation between lane width and vehicle speed ($P=0.022$). The Pearson correlation coefficient was found to be –0.099, indicating that there is a weak, negative correlation between lane width and vehicle speed (Appendix E, Table E.9). The regression itself has a p-value of 0.044 (Appendix E, Table E.11), meaning that there is indeed a significant relationship between lane width and vehicle speed (based on the 95% confidence interval). The (unstandardised) regression coefficient was found to have a value of –1.061, which can be interpreted as follows: For every meter increase in lane width, vehicle speed decreases by 1.061 km/h. It must be noted, however, that the regression model has a very low R-squared value (0.01; 0.007 adjusted), implying that variances in vehicle speeds is only minimally explained by differences in lane width, and that these variances can be better explained by other factors or road characteristics (Appendix E, Table E.10).

Interestingly, the regression results for speeds driven on 50 km/h roads were found to be the opposite. The correlation between lane width and vehicle speed was also found to be significant ($P<0.001$), however the Pearson correlation coefficient in this case was found to be 0.618, indicating a moderate, positive correlation between lane width and vehicle speed (Appendix E, Table E.12). The regression model has a p-value smaller than 0.001 (Appendix E, Table E.14), meaning that the relationship between lane width and vehicle speed is significant (based on the 95% and 99% confidence intervals). The regression coefficient was found to have a value of 5.608, which means that for every meter increase in lane width, vehicle speed increases by 5.608 km/h. The model has an R-squared value of 0.382 (0.378 adjusted), which is fairly low but is still higher than the R-squared value of the 30 km/h regression model, implying that lane width explains more of the variances in vehicle speeds on 50 km/h roads than on 30 km/h roads (Appendix E, Table E.13).

As the results of each linear regression model would suggest, the effect of lane width on vehicle speeds seems to be different for each speed limit category. On 50 km/h roads, the effect of lane width on vehicle speeds lines up with theoretical and empirical expectations, however contradictory evidence was found on 30 km/h roads. This may imply that, particularly for 30 km/h roads, lane width is not the most significant determinant of vehicle speeds, and that other factors or road characteristics may be much more significant in explaining variances in vehicle speeds as opposed to lane width. For this reason, it may be more useful to examine the interaction effects between lane width and other road characteristics as these effects may better explain the differences in vehicle speeds on 30 km/h roads. The effects of these interactions are further explored in the following sub-section (Combined road characteristic effects on vehicle speeds). For now, individual road characteristics will continue to be examined, and the following road characteristic analysed may arguably have profound interactions with lane width.

Lane markings

The presence of lane markings was also found to have significant effects on vehicle speed, according to previous studies. These studies found that lane markings contribute to higher vehicle speeds. To determine if these findings also apply to this research context, two-sample t-tests were conducted that compares the mean speeds on roads with lane markings and on roads without lane markings.

On 30 km/h roads, the two-sample t-test results show that the mean V85 speeds are significantly different between the two lane marking categories ($P<0.001$; shown in Appendix E, Table E.16). It was found that on average, drivers tend to drive faster on roads without lane markings than on roads with lane markings, with a mean speed difference of approximately 11 km/h (Appendix E, Table E.15). The main issue with these results, however, is that there was only one 30 km/h road segment that had lane markings while all the other road segments did not have any lane markings, leading to a potentially biased and unreliable result (Type I error, or a false-positive result). The statistically significant result of this t-test should therefore be taken with a grain of salt, as the true effects of lane markings on vehicle speed may not be entirely known given the low number of cases pertaining to road segments with lane markings present.

As for the effects of lane markings on vehicle speed on 50 km/h roads, the two-sample t-test shows different results compared to the one conducted for 30 km/h roads. The test results show that there is no significant difference in mean speeds between the two lane marking categories ($P>0.05$), meaning that lane markings have no significant effect on vehicle speed (Appendix E, Table E.18). Because the number of road segments with and without lane markings are nearly balanced, the risk of receiving a Type II error (false-negative) is minimised and the result can therefore be considered reliable.

Both t-test results contradict previous findings regarding the effects of lane markings on vehicle speed, but given that the results of the 30 km/h t-test may lack validity, it is difficult to conclude whether or not the presence of lane markings actually reduce vehicle speeds on 30 km/h roads. And as for 50 km/h roads, the presence of lane markings on its own may not have any significant effect on vehicle speeds, but it may potentially have significant effects in combination with other road characteristics, such as lane width (which will be further discussed in the following sub-section).

Road surface

Road surface is another road characteristic that may potentially have significant effects on vehicle speed. According to previous studies, people tend to drive faster on roads paved with asphalt than on other road surface types, such as brick. To find out if this also applies to this research context, a mix of one-way ANOVA and two-sample t-test were utilised to determine if there are differences in mean speeds between different road surfaces. One-way ANOVA is conducted for 30 km/h roads (as there are three road surface categories found on these roads), while the two-sample t-test is conducted for 50 km/h roads (only two road surface categories were found on these roads).

The results of the one-way ANOVA show that there are significant differences in mean speeds between the three road surface categories on 30 km/h roads ($P<0.001$; shown in Appendix E, Table E.20). Examining these differences even further, post-hoc tests reveal that these differences primarily stem from speed differences between grey asphalt and brick, as well as between grey asphalt and dyed asphalt. These post-hoc tests also reveal that there is no significant difference in mean speeds between brick and dyed asphalt. Based on these results, it can be concluded that people, on average, drive faster on roads paved with grey asphalt than on the other two road surface types, while changing the road surface from brick to dyed asphalt (and vice versa) would have no significant effect on vehicle speed.

Regarding 50 km/h roads, the results of the two-sample t-test show that there is no significant difference in mean speeds between brick-paved roads and (grey) asphalt-paved roads ($P>0.05$). This indicates that road surface has no significant effect on vehicle speed, and changing the road surface would therefore not contribute to a reduction in vehicle speeds on 50 km/h roads (Appendix E, Table E.22).

The results of the ANOVA confirm prior understanding of road surface effects on vehicle speeds. It can be said that for 30 km/h roads in particular, road surface can have a significant impact on speed limit credibility. However, the same cannot be said for 50 km/h roads, as the results of the t-test have shown. It would therefore be interesting to see if any interactions between road surface and other road characteristics would potentially have significant effects on speeds driven on 50 km/h roads, as manipulating the road surface itself would not make any difference regarding the credibility of a 50 km/h speed limit.

Bike lanes

The presence of bike lanes is a unique and interesting road characteristic that could potentially have a profound impact on driving behaviour. It is hypothesised that an increase in the degree of separation of bike lanes from the main carriageway would lead to an increase in vehicle speeds. In order to test this hypothesis, the same procedure of hypothesis testing was carried out as was done previously for the effects of road surface on vehicle speed. One-way ANOVA was conducted for bike lane effects on 30 km/h roads (four bike lane categories), while a two-sample t-test was conducted for 50 km/h roads (two bike lane categories).

The results of the ANOVA show that there are significant differences in mean speeds between the four bike lane categories on 30 km/h roads ($P<0.001$; shown in Appendix E, Table E.24). Post-hoc tests reveal that the most significant differences can be found between roads with no bike lanes present and roads with bicycle gutters present. Vehicle speeds tend to be higher on roads with bicycle gutters than on roads without any bike lanes (Appendix E, Table E.23). The effects of mixed bike lane characteristics (i.e. roads that have a mix of a bicycle gutter in one direction and no bike lane/separated bike lane in the other direction) were found to be insignificant, which may be a result of the relatively low number of cases (i.e. lack of road segments) observed in those respective categories.

Similarly, for 50 km/h roads, the two-sample t-test reveals significant differences in mean vehicle speeds between roads with bicycle gutters and those with separated bicycle paths ($P<0.001$; shown in Appendix E, Table E.26). The results indicate that vehicle speeds are higher on roads with bicycle gutters compared to roads with separated bike paths (Appendix E, Table E.25). This finding aligns with the notion that the presence of bicycle gutters may actually reduce speed limit credibility, while the presence of separated bike lanes would have the opposite effect.

The results of both tests revealed that the incorporation of bicycle gutters into road design would lead to higher vehicle speeds overall, regardless of what the speed limit is. For 30 km/h roads, the results of the ANOVA align with the hypothesis that a higher degree of bike lane separation would lead to an increase in vehicle speeds. However, the opposite was found to be true for 50 km/h roads. This is an interesting finding as it does not conform to theoretical expectations and prior empirical evidence. There could be several reasons for this finding, one potentially being the fact that bicycle gutters are far more common than separated bike paths (true for this particular case study, at least), therefore this finding may possibly be a result of a lack of data regarding vehicle speeds on roads with separated bike lanes. The influence of other road characteristics should not be ruled out however, as other road characteristics may potentially explain the significant differences in vehicle speeds between the two bike lane categories, and why people tend to drive slower on roads with separated bike lanes than on roads with bicycle gutters.

On-street parking

The final road characteristic to be analysed in this sub-section pertains to the presence of on-street parking. The hypothesis regarding its effects on vehicle speed is that the presence of on-street parking would lead to a reduction in vehicle speeds. This hypothesis is tested by conducting two-sample t-tests for each speed limit category, in which mean vehicle speeds are compared between roads with on-street parking and roads without on-street parking.

The results of both t-tests show that there are significant differences in mean speeds between the two on-street parking categories ($P<0.05$; shown in Appendix E, Tables E.28 and E.30). For both 30 km/h and 50 km/h roads, vehicle speeds tend to be higher on roads with on-street parking than on roads without on-street parking (Appendix E, Tables E.27 and E.29). These findings are contradictory to the hypothesis that on-street parking would slow down vehicle traffic, and the impact of on-street parking would therefore have negative ramifications on speed limit credibility. It is worth noting, however, that the magnitude of on-street parking effects on vehicle speeds is much greater on 50 km/h roads than on 30 km/h roads, implying that on-street parking would have a larger impact on the credibility of a 50 km/h speed limit than on a 30 km/h speed limit. The limited magnitude of on-street parking effects on 30 km/h roads may be a result of an unbalanced sample, as on-street parking is a very common characteristic of 30 km/h roads, hence the lack of road segments without on-street parking may reduce the validity of the results and its true effects may not be entirely known. Of course, as is the case with most of the road characteristics analysed in this sub-section, the influence of different road characteristic combinations cannot be ruled out as they may provide a better explanation for these unexpected findings.

Summary

Table 4.1 presents a summary of the results of each road characteristics' effect on vehicle speed.

Table 4.1. Summary of road characteristic effects on vehicle speed.

Road characteristic	**Test method(s)**	**30 km/h speed limit**	**50 km/h speed limit**
Speed limit	*One-sample t-test*	*Significant difference; mean speed higher than speed limit*	*Significant difference; mean speed lower than speed limit*
One-way street	*Two-sample t-test*	*Significant effect; mean speed higher on one-way streets*	*Significant effect; mean speed lower on one-way streets*
Lane width	*Linear regression*	*Weak negative relationship between speed and lane width; low R squared*	*Moderate positive relationship between speed and lane width; low R squared but higher than for 30 km/h roads*
Lane markings	*Two-sample t-test*	*Significant effect; mean speed lower on roads with lane markings (possible Type I error due to low sample size)*	*No significant effect on vehicle speed*
Road surface	*One-way ANOVA (30 km/h roads); two-sample t-test (50 km/h roads)*	*Significant effects; mean speed higher on grey asphalt roads than on brick and dyed asphalt roads. No significant difference between brick and dyed asphalt*	*No significant effect on vehicle speed*
Bike lanes	*One-way ANOVA (30 km/h roads); two-sample t-test (50 km/h roads)*	*Significant effects; mean speed higher on roads with bicycle gutters than on roads with no bike lanes. Effects of mixed bike lane characteristics not significant*	*Significant effect; mean speed higher on roads with bicycle gutters than on roads with separated bike paths*
On-street parking	*Two-sample t-test*	*Significant effect; mean speed higher on roads with on-street parking (possible Type I error due to high sample imbalance)*	*Significant effect; mean speed higher on roads with on-street parking (effect more profound than on 30 km/h roads)*

4.1.4. Combined road characteristic effects on vehicle speeds

The previous sub-section presented an examination of road characteristics and their individual effects on vehicle speed, without taking into account of the joint effects of road characteristic combinations. In this sub-section, the joint effects are examined in order to gain a fuller and a more holistic understanding of how the relationships between different road characteristics affect vehicle speeds as a whole. For this purpose, a General Linear Model (GLM) was conducted to examine the effects of various road characteristics on vehicle speed. The independent variables in the model include all of the previously examined road characteristics, namely speed limit (30 km/h vs. 50 km/h), one-way street presence (yes/no), lane markings (yes/no), road surface type (brick, dyed asphalt, grey asphalt), presence and type of bike lanes (none, gutter, separated), presence of on-street parking (yes/no), and lane width (in meters). The results of the GLM and the statistical figures referenced throughout this sub-section can be found in Tables 4.2 and 4.3, and the full SPSS results can be seen in Appendix F.

The overall model was found to be statistically significant ($p<0.001$), indicating that the included characteristics explain a significant portion of the variance in vehicle speeds. The model accounted for 21.2% of the variance in speed ($R^2=0.212$, adjusted $R^2=0.197$), suggesting that while the predictors have a meaningful effect, additional random and unobserved factors may also influence speed.

Speed limit had the strongest effect on vehicle speed, with significantly lower speeds observed on 30 km/h roads compared to 50 km/h roads ($F=24.192$, $p<0.001$). Additionally, the beta coefficient was found to be –7.595 for roads with a 30 km/h speed limit, meaning that vehicle speeds decrease by 7.595 km/h when the speed limit changes from 50 km/h to 30 km/h (50 km/h is the reference category in this case).

The presence of lane markings was also a significant predictor, with roads lacking lane markings associated with higher vehicle speeds ($F=7.207$, $p=0.007$). The beta coefficient for this parameter was found to be 5.028, meaning that vehicle speeds increase by 5.028 km/h when lane markings are removed (roads with lane markings used as reference).

The presence and nature of bike lanes had a statistically significant effect on speed ($F=6.011$, $p<0.001$), though specific pairwise comparisons did not reach significance at the conventional threshold. Roads with no bike lanes tended to have lower speeds compared to those with separated bike paths ($B=-5.919$, $p=0.054$), however no significant difference in speeds were found between roads with bicycle gutters and roads with separated bike paths ($B=0.390$, $p=0.879$).

Similarly, lane width was positively associated with vehicle speed, with each additional meter of lane width corresponding to a 1.835 km/h increase in speed ($F=5.492$, $B=1.835$, $p=0.019$).

Road surface type showed a marginal effect on speed ($F=2.504$, $p=0.083$), with brick roads associated with slightly lower speeds compared to grey asphalt ($B=-2.470$, $p=0.029$). However, dyed asphalt did not significantly differ from grey asphalt ($B=-0.516$, $p=0.794$).

The presence of on-street parking and whether the road was a one-way street did not have a statistically significant effect on speed ($F=0.543$, $p=0.462$; $F=0.293$, $p=0.589$, respectively).

In summary, speed limit, lane markings, presence of bike lanes, and lane width were all significant predictors of vehicle speed. The absence of lane markings and wider lanes were associated with higher speeds. Roads with no bike lanes showed a trend toward lower speeds compared to those with separated bike paths, though the effect was marginally significant. Road surface type had a small effect, with brick roads showing slightly lower speeds than grey asphalt. The effects of on-street parking and one-way street design were not significant.

Table 4.2. Tests of Between-Subjects Effects.

Road characteristic	F-value	p-value
Speed limit	24.912	<.001
One-way street	0.293	0.589
Lane markings	7.207	0.007
Road surface	2.504	0.083
Bike lanes	6.011	<.001
On-street parking	0.543	0.462
Lane width	5.492	0.019

Table 4.3. Parameter Estimates.

Predictor	B	SE	t-value	p-value
Intercept	39.419	3.836	10.275	<.001
Speed limit (30 km/h)	-7.595	1.522	-4.991	<.001
One-way street (No)	-0.854	1.579	-0.541	0.589
Lane markings (No)	5.028	1.873	2.685	0.007
Road surface (Brick)	-2.470	1.127	-2.191	0.029
Road surface (Dyed asphalt)	-0.516	1.975	-0.261	0.794
Bike lanes (None)	-5.919	3.071	-1.927	0.054
Bike lanes (Gutter/none)	-7.124	3.748	-1.901	0.058
Bike lanes (Gutter)	0.390	2.570	0.152	0.879
Bike lanes (Gutter/separated)	-3.035	3.421	-0.887	0.375
On-street parking (No)	-1.225	1.662	-0.737	0.462
Lane width	1.835	0.783	2.343	0.019

Model Summary: $R^2 = 0.212$, Adjusted $R^2 = 0.197$, $F = 14.189$, $p < .001$

4.1.5. Comparative analysis of individual and combined road characteristic effects on vehicle speeds

Comparing the GLM results with the individual test results from the previous sub-section shows some similarities and differences in terms of significance and direction of road characteristic effects on vehicle speeds. For starters, speed limit showed strong significant effects on vehicle speeds in both cases. While the GLM output indicates that lower speed limits would lead to a general reduction in vehicle speeds, the one-sample t-test results show that drivers, on average, still drive faster than the 30 km/h speed limit, indicating a compliance issue on 30 km/h roads. While lower speed limits may promote safer driving speeds to a certain extent, these results show that speed limits on their own would not sufficiently enforce and encourage speed limit compliance, and that other road characteristics would have to play a more significant role in ensuring that drivers comply with the speed limit, particularly on roads with a 30 km/h speed limit.

Lane width was another road characteristic that was found to have significant effects, according to both the GLM and linear regression outputs. In both the GLM and 50 km/h linear regression outputs, lane width was found to have a positive relationship with vehicle speed. However, an inverse relationship was found on 30 km/h roads. This may be due to differences in road design between 30 km/h and 50 km/h roads, as 30 km/h roads have the tendency to be wider to accommodate on-street parking, and the presence of on-street parking would make the road visually narrower, resulting in lower vehicle speeds. This could also be explained by the low R squared statistic in the 30 km/h regression model, as this statistic implies that other (unobserved) factors would better explain the variation in vehicle speeds on 30 km/h roads. The inverse relationship between lane width and vehicle speed on 30 km/h roads should therefore be taken with a grain of salt, as this relationship may not reflect the true effects of lane width on vehicle speeds in general and should only be taken into consideration in combination with other factors, as the GLM output would suggest.

The effect of lane markings on vehicle speed was found to be significant in both the GLM and the 30 km/h two-sample t-test, but not for the 50 km/h t-test. In both cases where the effect of lane markings has reached statistical significance, higher vehicle speeds were observed on roads without lane markings, whereas the presence of lane markings on 50 km/h roads were found to be negligible. This would imply that the presence of lane markings has a much greater influence on vehicle speeds driven on 30 km/h roads than they do on 50 km/h roads, and their presence would therefore have greater ramifications on the credibility of a 30 km/h speed limit than of a 50 km/h speed limit. However, it is worth noting that the significance of lane markings on 30 km/h roads may be due to a Type I error as a result of low sample size, and this error may have been carried over to the GLM, so the effect of lane markings on vehicle speed may not be as profound as initially portrayed.

Road surface was also shown to have significant effects on vehicle speed in both the GLM and one-way ANOVA conducted for 30 km/h roads, but no significant effects were found in the two-sample t-test conducted for 50 km/h roads. Both the GLM and ANOVA analyses revealed that roads paved with grey asphalt resulted in higher vehicle speeds compared to brick-paved roads, but no significant differences in speed were found between grey asphalt and dyed asphalt, as well as between brick and dyed asphalt. This would imply that the use of dyed asphalt would not lead to a significant reduction in vehicle speeds as opposed to the use of brick surfaces and would therefore not contribute meaningfully to improving the credibility of a 30 km/h speed limit. It should also be mentioned, however, that there were a limited number of road segments examined in the analysis that used dyed asphalt surfaces, which makes it difficult to determine what their real effects on speed are when compared to other road surface types. Just as is the case with lane markings, the non-significant findings from the 50 km/h two-sample t-test suggests that the manipulation of road surfaces as a strategy to influence and reduce vehicle speeds would be much more effective on 30 km/h roads than on 50 km/h roads, and would thus have a greater impact on the credibility of a 30 km/h limit.

The presence and nature of bike lanes showed significant effects across the board, with significant differences in vehicle speeds found in the GLM, the 30 km/h one-way ANOVA and the 50 km/h two-sample t-test. Both the 30 km/h and 50 km/h tests showed higher vehicle speeds on roads with bicycle gutters present, while the GLM showed that the absence of bike lanes resulted in a marginally significant reduction in vehicle speeds. These results indicate that the inclusion of bicycle gutters may not be appropriate for the design of 30 km/h roads, as the tendency to drive faster on roads with bicycle gutters would diminish the credibility of a 30 km/h speed limit. The absence of bike lanes would appear to have the most potential towards the realisation of the goal of improving compliance, and therefore credibility, of a 30 km/h speed limit, even though this effect is marginally significant. The effects of mixed bike lane characteristics were found to be insignificant in any of these cases.

The effects of one-way streets and on-street parking were not found to be significant according to the GLM, but they did have significant effects in the individual t-tests. Due to this contradiction in findings, as well as the fact that the GLM results hold more weight than the individual test results, no definitive inferences can be made about the true effects of one-way streets and on-street parking presence on vehicle speeds as a whole. It may therefore be assumed that the presence of one-way streets and on-street parking would not significantly improve or diminish speed limit credibility, particularly that of a 30 km/h limit.

4.2. Analysis of road characteristic effects on speed limit credibility perception

The previous chapter attempted to give an answer to the second sub-research question by examining the real-world effects of various road characteristics on vehicle speeds, providing an objective measure of how different road characteristics can potentially affect speed limit credibility. In this chapter, the focus will be on providing an answer to the third sub-research question, which delves into the subjective aspects of speed limit credibility by examining how road characteristic variations influence drivers' perceptions regarding the actual speed limit, their sense of safety and how credible they perceive a given speed limit is on a given road segment. By examining factors such as lane width, presence of lane markings, road surface type, and bicycle infrastructure, the analysis aims to identify which elements contribute to a speed limit being perceived as reasonable or unrealistic. Understanding these relationships can provide valuable insights for road design and policymaking, ultimately supporting the development of more effective speed management strategies.

This chapter is structured as follows: First, the demographic characteristics of survey respondents are discussed. Second, the associations between road characteristics and speed limit perception are explored. Third, the associations between road characteristics and perceived safety are presented. And finally, the associations between road characteristics and speed limit credibility perception are delved into.

4.2.1. Descriptive results of survey respondent characteristics

As laid out in the research methodology, an online survey was conducted to collect data regarding people's perceptions about road safety and speed limit credibility. The survey included questions about respondent demographics, such as age, gender, preferred mode of transport, possession of a driver's license, car ownership, and so on. The survey received a total of 83 responses, far surpassing the initial goal of 50 responses.

The majority of respondents were male, roughly making up approximately 57% of the survey sample, compared to the 43% that were female. Figure 4.17 shows the percentage distribution of each gender in a pie chart.

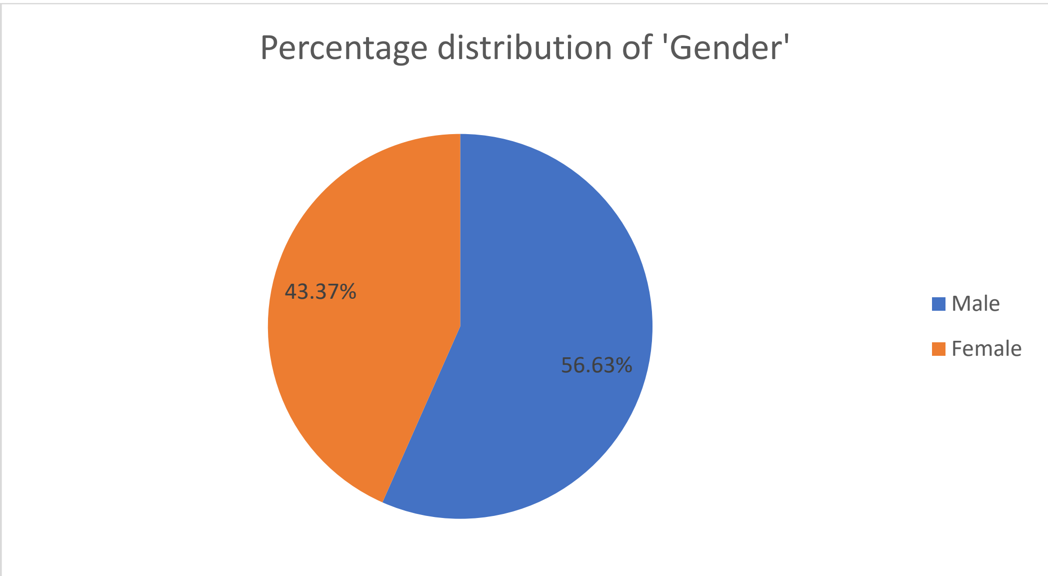

Figure 4.17. Percentage distribution of gender among survey respondents.

As for the age distribution of respondents, there is a wide spread of age ranges among the sample. The age bracket with the highest number of respondents is those between the ages of 55 and 64 (28.92%), followed by those between the ages of 18 and 24 (19.28%). Respondents who are between the ages of 25 and 34 account for 18.07% of the sample, while those who are aged between 35 and 44 and those between 45 and 54 equally account for 12.05%. The age group with the least number of respondents are those above the age of 65 (9.64%). Figure 4.18 shows these percentage distributions on a pie chart.

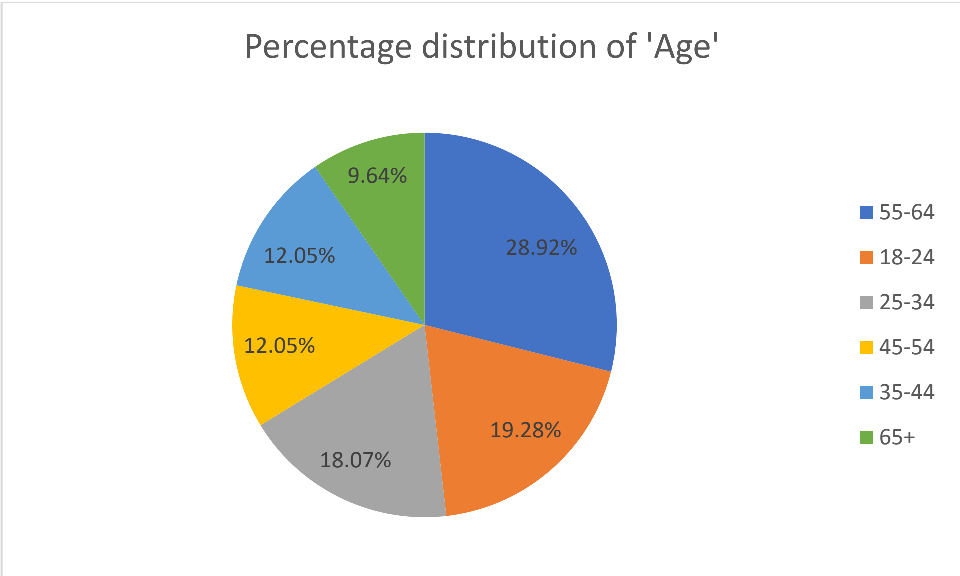

Figure 4.18. Percentage distribution of age among survey respondents.

When asked about the most frequently used mode of transport, the majority of respondents stated that they drive a car most often (57.32%). This is reflected by the fact that around 90% of respondents have a driver's license and 73% own a car (shown in Figures 4.20 and 4.23, respectively). The second most frequently used mode of transport is the bicycle, with 23.17% of respondents using the bike as their primary mode of transport, followed by public transport at 10.98%. Other transport modes (walking, motorcycle, e-bike) together make up the remaining 9%. These distributions are shown in Figure 4.19.

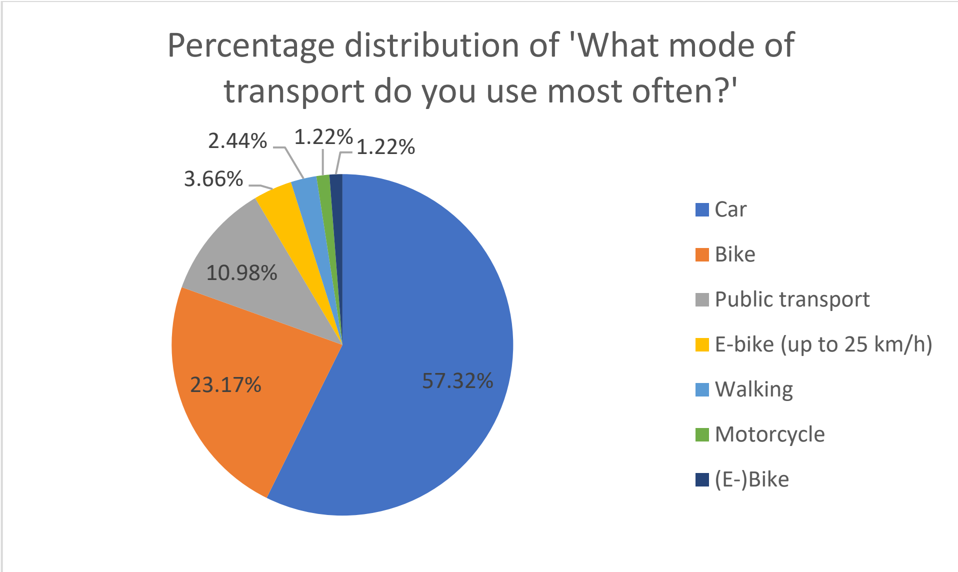

Figure 4.19. Percentage distribution of primary transport modes among survey respondents.

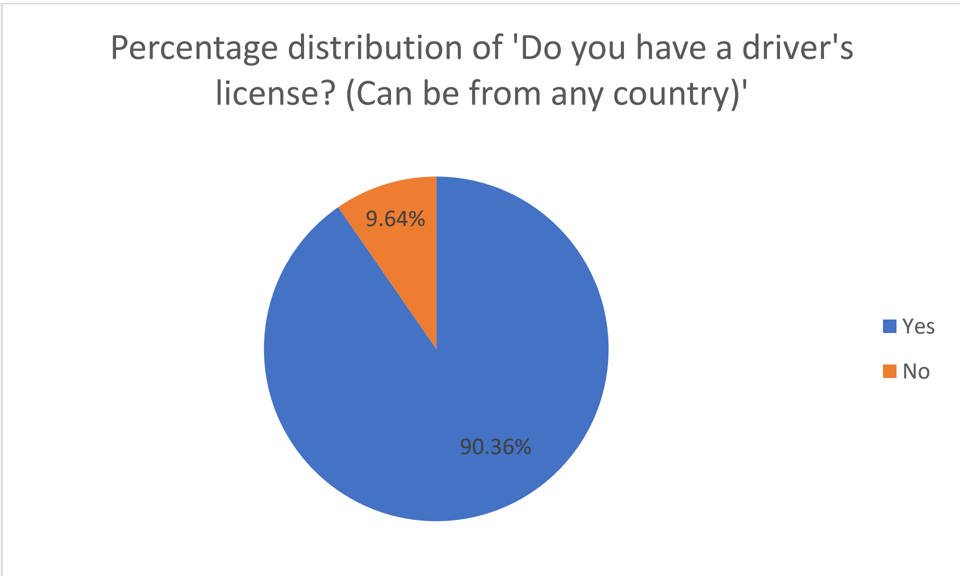

Figure 4.20. Percentage distribution of driver's license possession among survey respondents.

Out of the 90% of respondents that are in possession of a driver's license, the vast majority (73.33%) have more than 10 years of driving experience. This correlates to the age distribution of the survey sample, in which the majority of respondents are over the age of 35 (more than 10 years from the legal driving age of 18, assuming that the respondents obtained their licenses between the ages of 18 and 24). 12% of respondents, the second biggest group, have 2 to 4 years of driving experience, reflected by the significant 18 to 24 age demographic in the sample. The remaining 15% of respondents have driving experiences ranging from 4 to 10 years. Figure 4.21 displays these distributions in a pie chart.

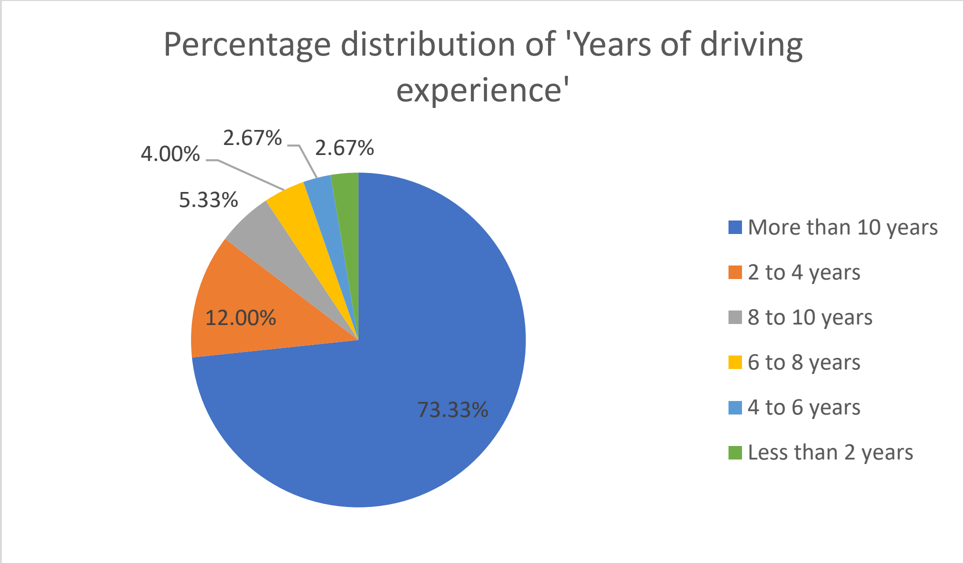

Figure 4.21. Percentage distribution of years of driving experience among survey respondents.

A significant majority of respondents that have a driver's license drive regularly, with 42.67% driving every day and 34.67% driving a few times a week. These proportions align with the relatively high rate of car ownership among the survey sample and the fact that most respondents use a car as their primary mode of transport. The percentage of respondents that drive occasionally (a few times a month) or rarely (a few times a year) are equally distributed at 9.33% each. The remaining 4% of respondents do not drive at all, even though they are in possession of a driver's license, therefore they most likely do not own a car and instead use other means of transport to get around. These distributions are graphically displayed in Figure 4.22.

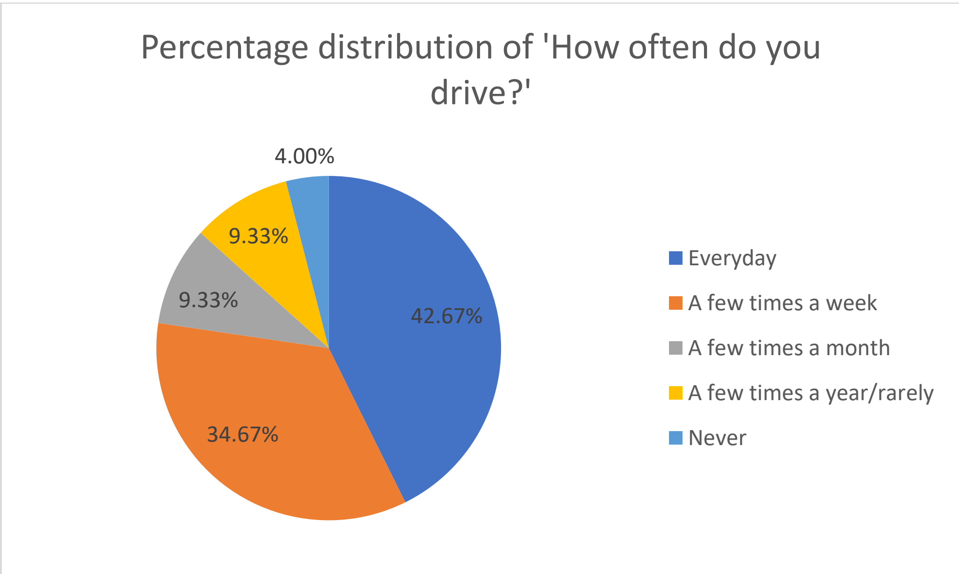

Figure 4.22. Percentage distribution of driving frequency among survey respondents.

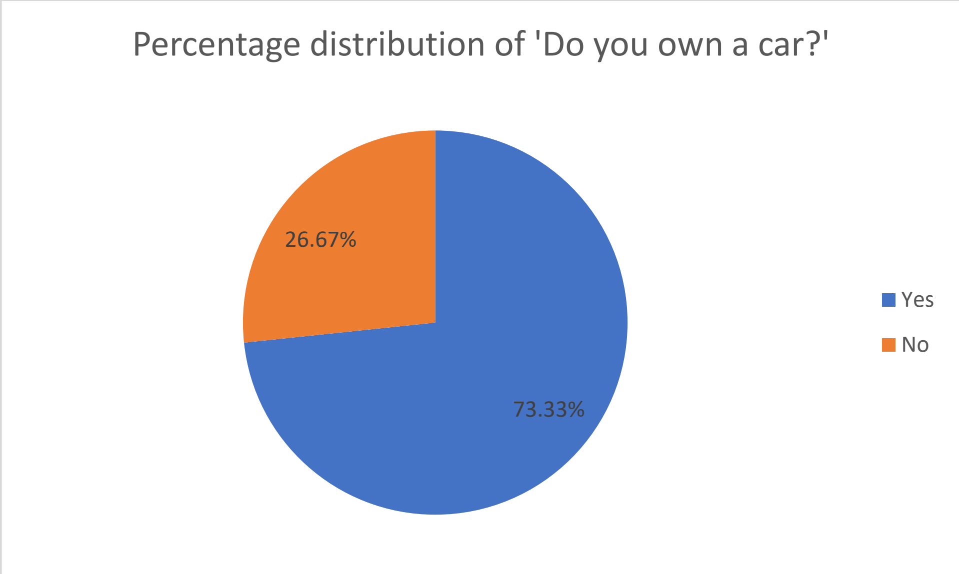

Figure 4.23. Percentage distribution of car ownership among survey respondents.

The demographic results of the survey showed that most of the respondents are experienced drivers and tend to drive regularly, with many of them using the car as their main mode of transport. These respondents therefore have a good understanding of the driving environment in the Netherlands and are aware of the differences between various road types, in terms of their design and the speed limit that can be expected from these different road designs. Their perceptions on speed limits, safety and credibility would make a meaningful contribution to a better understanding of how road design influences driving behaviour and how speed limits can be made more credible based on their subjective interpretation of the road environment. These perceptions are further analysed in the following sub-sections with the aim of determining which road characteristics would have the largest impact on speed limit credibility perception, and how these characteristics can therefore be altered to improve the credibility of a speed limit.

4.2.2. Associations between road characteristics and speed limit perception

In order to understand how road design influences drivers' perception of speed limit credibility, it is important to first look at how drivers perceive what speed limits are appropriate given the design of a road. A significant factor of speed limit credibility is the perception that drivers have regarding the "correct" speed that should be driven on a road based on how the road is designed and laid out, including the type of characteristics that shape the road environment. If perceptions regarding appropriate speeds do not match the actual speed limit, then the speed limit is not considered to be credible. In this section, these perceptions will be examined more in depth to identify which design elements contribute to higher or lower perceived speed limits and whether certain road features lead to discrepancies between posted and perceived speed limits. These insights can help inform road design strategies that enhance speed limit credibility and promote safer driving behaviour.

Data on speed limit perception was collected through the online survey in which respondents were shown eight different images of various road designs, each with varying road characteristics to ensure heterogeneity among the selected road segments for this experiment and to ensure the ability to make inferences about the influence of certain road characteristics on speed limit perception. Respondents were then asked to select which speed limit they thought was most appropriate for that particular road segment, without knowing what the actual speed limit was. This was presented as a multiple-choice question in which respondents were given three choices: 30 km/h, 50 km/h, or “other” (which was left open-ended so respondents could manually type in the speed limit they thought was most appropriate in case they thought the other two choices were not suitable). The responses were then aggregated and analysed based on individual road characteristics that are commonly shared among the road scenarios, in which the Pearson Chi-Square test is used to test for statistically significant associations between road characteristics and speed limit perception. Furthermore, an Ordinal Logistic Regression was also conducted to determine the direction and magnitude of the effects of road characteristics on speed limit perception. This would allow the results to be quantifiable and inferences can therefore be made about the significance of road characteristics on how drivers perceive speed limits, and whether certain characteristics can lead to higher or lower perceptions of speed limit credibility.

The results of the individual chi-square tests were all found to be statistically significant ($p<0.001$), meaning that associations do exist between road characteristics and speed limit perception. The downside of these tests, however, is that they do not reveal any information about the direction and magnitude of these associations, hence this information will be derived from graphical interpretation of the results (along with logistic regression results). These graphical representations and chi-square test results can be found in Appendix G. Based on these results, the relationships between road characteristics and speed limit perception can be summarised in the following points:

- **Speed limit:** The majority of respondents correctly associated 30 km/h roads with a 30 km/h speed limit, and 50 km/h roads with a 50 km/h speed limit, implying that the overall design of a road has a positive effect on speed limit perception.
- **One-way street:** The majority of respondents associated one-way streets with a 30 km/h speed limit, and bi-directional roads with a 50 km/h speed limit, although a significant number of respondents associated bi-directional roads with a 30 km/h speed limit.
- **Lane width:** Respondents primarily associated wider lane widths with a lower speed limit (30 km/h), while narrower lane widths are associated with a higher speed limit (50 km/h), implying an inverse relationship between lane width and speed limit perception.
- **Lane markings:** Most respondents associated roads without lane markings to have a 30 km/h speed limit, and roads with lane markings to have a 50 km/h speed limit.
- **Road surface:** Most respondents associated brick roads with a 30 km/h speed limit, and asphalt roads with a 50 km/h speed limit.
- **Bike lanes:** Respondents primarily associated roads without bike lanes to have a 30 km/h speed limit, and roads with gutter and/or separated bike lanes to have a 50 km/h speed limit.
- **On-street parking:** The majority of respondents associated roads with on-street parking to have a 30 km/h speed limit, and roads without on-street parking to have a 50 km/h speed limit.

To gain further insight into the direction and magnitude of these associations when taking every road characteristic into account, an ordinal logistic regression was conducted. Given the ordinal nature of the dependent variable (speed limit perception), an ordinal logistic regression was considered to be the most appropriate statistical test for this analysis. The results of the regression would provide information regarding the probability that a respondent would perceive a speed limit to be higher or lower based on a change in a certain road characteristic. The regression output provides logit, or log odds, parameter estimates of each (category of a) road characteristic as a measure of their association with speed limit perception (known as a B coefficient), along with their corresponding p-values (see Appendix H, Table H.1 for full SPSS output). These B coefficients were manually calculated into odds ratios (by taking the natural exponent of the B coefficient) in order to simplify interpretation of the results. These figures (B coefficients, their corresponding odds ratios, and p-values) are shown in Table 4.4.

Table 4.4. Logistic regression results of speed limit perception.

Road Characteristic	B Coefficient	Odds Ratio (Exp(B))	p-value
Lane width	-0.325	0.723	0.619
One-way street (no)	-0.646	0.524	0.148
Lane markings (no)	-1.264	0.282	0.134
Road surface (asphalt)	2.698	14.848	0.014 (significant)
Bike lanes (none)	-3.910	0.020	0.045 (significant)
Bike lanes (gutter)	-1.990	0.137	0.259
Bike lanes (mixed gutter/separated)	-2.855	0.058	0.162

The results of the ordinal logistic regression indicate that road surface type and the absence of bike lanes have statistically significant effects on speed limit perception (both with p-values smaller than 0.05). The coefficient for road surface is positive, meaning that roads paved with asphalt are 1,384.8% more likely to be perceived as having a higher speed limit compared to the reference category (brick roads). In contrast, the absence of bike lanes has a strong negative effect, meaning that roads without bike lanes are associated with a 98% decrease in the odds of perceiving a higher speed limit.

Other factors, including lane width, one-way streets, and lane markings, did not have statistically significant effects on speed limit perception. However, the odds ratios suggest some trends: for every unit increase in lane width, the odds of perceiving a higher speed limit decrease by 27.7%; bi-directional roads reduce the odds by 47.6% as opposed to one-way streets; and the absence of lane markings decreases the odds by 71.8%. While these effects appear meaningful, the non-significant p-values indicate that these relationships could be due to random variation rather than systematic differences in perception.

Similarly, different bike lane configurations also did not have significant effects. Compared to roads with separated bike paths, roads with bike lane gutters decrease the odds of perceiving a higher speed limit by 86.3%, and mixed bike lanes with a combination of a gutter and a separated lane decrease the odds by 94.2%, though these effects were not statistically significant. The logistic regression did not provide a B coefficient for the presence of on-street parking, possibly due to overlapping with other road characteristics, therefore the true effects of on-street parking on speed limit perception cannot be definitively determined.

Overall, these findings suggest that road surface and the presence (or absence) of bike lanes are key design factors influencing how drivers perceive speed limits, while lane width, one-way streets, lane markings, and specific bike lane configurations appear to have less of an impact. However, given the non-significant results for some predictors, further research with a larger sample size may be necessary to confirm these trends.

4.2.3. Associations between road characteristics and safety ratings

As laid out in the theoretical framework (Figure 3.3), an important contributing factor to speed limit credibility is the perceived safety of the driving environment. If a driver perceives that the road can be safely driven on at a given speed limit, then the credibility of that particular speed limit increases. However, if a driver perceives that the road is unsafe for driving at that speed limit, then the credibility of that speed limit decreases. In this section, the road characteristic effects on safety perception are analysed, which aims to identify what road design elements contribute to a higher or lower safety perception score, and ultimately, how these elements contribute to an improvement or a reduction in speed limit credibility.

For each of the eight road design scenarios shown in the survey, respondents were asked to give a safety rating regarding how safe they would feel driving on the pictured road at a certain speed limit. The safety rating is based on a Likert scale ranging from 1 (very unsafe) to 5 (very safe), and respondents were asked to give a safety rating for a particular road according to four different speed limit categories: Less than 30 km/h, 30 km/h, 50 km/h, and more than 50 km/h. These speed limit categories were given in order to assess the effects of road characteristics on perceived safety more meaningfully and are irrespective of the actual speed limit posted for each road scenario, as safety perceptions can differ significantly if a particular road had a speed limit of 50 km/h instead of 30 km/h, or vice versa. Ordinal logistic regression was used to analyse the responses, which would reveal how changes to certain road design characteristics can positively or negatively influence safety perception, according to a given speed limit.

The regression results will primarily focus on safety perception ratings given under the 30 km/h and 50 km/h speed limit scenarios, as the effects of road characteristics on perceived safety were found to be the most profound under those speed limit scenarios and, given that this study mainly focused on roads with 30 km/h and 50 km/h speed limits, the results would have direct implications on the credibility of 30 km/h and 50 km/h speed limits. The safety ratings for speed limits under 30 km/h and over 50 km/h are briefly touched upon, although it is already worth mentioning that, for safety ratings over the 50 km/h speed limit, none of the road characteristics were found to have significant effects on safety perception. The full SPSS regression outputs can be found in Appendix H (Tables H.2 to H.5).

The regression results indicate that several road characteristics significantly influence safety perception for speed limits below 30 km/h. Lane width has a negative association with safety perception, meaning that for every unit increase in lane width, the odds of perceiving the road as safer decrease by 65.4%. Similarly, roads without lane markings are perceived as less safe, with a 76.5% reduction in the odds of selecting a higher safety category. Interestingly, the absence of bike lanes is associated with significantly higher safety perception, indicating that roads without bike lanes are seen as much safer than those with other bike lane configurations. While gutter lanes or mixed lane configurations (gutter/separated) also showed increased odds of higher safety perception, these effects were not statistically significant. Other factors, such as one-way streets and road surface type, did not have a statistically significant effect on safety perception. These findings suggest that wider lanes and the absence of lane markings may contribute to lower safety perception, while the lack of bike lanes tends to be associated with higher perceived safety.

Table 4.5. Logistic regression results of safety perception below 30 km/h.

Road Characteristic	B Coefficient	Odds Ratio	p-value
Lane width	-1.062	0.346	0.049 (significant)
One-way street (no)	0.049	1.050	0.892
Lane markings (no)	-1.448	0.235	0.047 (significant)
Road surface (asphalt)	-1.518	0.219	0.117
Bike lanes (none)	3.634	37.864	0.043 (significant)
Bike lanes (gutter)	2.740	15.487	0.072
Bike lanes (mixed gutter/separated)	3.141	23.127	0.080

Regarding safety perception ratings for a 30 km/h speed limit scenario, the only statistically significant predictor was whether the street was one-way, where roads that were bi-directional had 46.2% lower odds of being perceived as safer. While not statistically significant, the road surface variable suggests that asphalt roads are more likely to be perceived as safer compared to brick roads, with nearly five times higher odds. The presence of bike lanes, particularly the lack thereof, those configured as gutter lanes, and those with a mixed configuration of gutter and separated lanes, all had negative coefficients, suggesting that roads that do not have a purely separated bike lane configuration are perceived as less safe, though these effects were not statistically significant. The lane width and lane markings variables also did not show significant effects. Overall, these findings suggest that road design elements, particularly one-way street configurations and, to some degree, road surfaces, may play a role in shaping perceptions of safety on 30 km/h roads.

Table 4.6. Logistic regression results of safety perception at 30 km/h.

Road Characteristic	B Coefficient	Odds Ratio	p-value
Lane width	0.271	1.311	0.564
One-way street (no)	-0.619	0.538	0.041 (significant)
Lane markings (no)	0.476	1.610	0.491
Road surface (asphalt)	1.604	4.973	0.065
Bike lanes (none)	-2.263	0.104	0.162
Bike lanes (gutter)	-2.001	0.135	0.143
Bike lanes (mixed gutter/separated)	-2.334	0.097	0.158

The results of the ordinal logistic regression for roads with a 50 km/h speed limit scenario indicate that road surface type and the presence of bike lanes significantly influence perceived safety. Roads with an asphalt surface are associated with a significantly higher perceived safety rating, meaning that drivers are 648% more likely to rate these roads as safer compared to roads with a brick surface. In contrast, the presence and type of bike lanes strongly affect safety perception in a negative direction. Roads without bike lanes are associated with a 97.5% decrease in the odds of selecting a higher safety perception category compared to roads with other bike lane configurations. Similarly, roads with bicycle gutters see an 91.8% decrease in the odds of a higher safety rating, while roads with a mix of bicycle gutters and separated bike paths experience a 96.1% decrease in the odds of being rated as safer. The presence of one-way streets approaches statistical significance, suggesting that two-way streets may be perceived as slightly less safe than one-way streets, with a 43% decrease in the odds of a higher safety rating. However, lane width and the presence of lane markings do not have significant effects on perceived safety. These findings highlight that certain design elements, such as road surface and bike lane configurations, play a crucial role in how safe drivers perceive a road to be at a 50 km/h speed limit. Specifically, the absence of bike lanes and the use of bicycle gutters are associated with a sharp decline in perceived safety, while an asphalt surface substantially increases the likelihood of a road being perceived as safe.

Table 4.7. Logistic regression results of safety perception at 50 km/h.

Road Characteristic	B Coefficient	Odds Ratio	p-value
Lane width	0.359	1.432	0.370
One-way street (no)	-0.563	0.570	0.053
Lane markings (no)	-0.124	0.883	0.825
Road surface (asphalt)	2.012	7.480	0.007 (significant)
Bike lanes (none)	-3.670	0.025	0.007 (significant)
Bike lanes (gutter)	-2.501	0.082	0.032 (significant)
Bike lanes (mixed gutter/separated)	-3.251	0.039	0.019 (significant)

A comparison of the ordinal logistic regression results for safety perception across different speed limits reveals notable similarities and differences in how road characteristics influence perceived safety. Road surface played a significant role, particularly for roads with a 50 km/h speed limit, where asphalt roads were associated with a more than seven-fold increase in the odds of perceiving the road as safer. However, for roads with speed limits under 30 km/h, asphalt had a negative, albeit non-significant, association with safety perception, while for 30 km/h roads, asphalt showed a positive trend but did not reach conventional significance. The presence and type of bike lanes also had differing effects across speed limits. On roads with a 50 km/h limit, the absence of bike lanes significantly reduced perceived safety, while bicycle gutters and mixed gutter/separated lanes also decreased safety perception. Conversely, for roads under 30 km/h, the presence of bike lanes, especially fully separated paths, did not significantly impact safety perception, whereas for 30 km/h roads, none of the bike lane configurations had significant effects. The influence of lane width was inconsistent across speed limits; while it had a marginally significant negative effect on safety perception for roads under 30 km/h, it showed no significant impact at 30 km/h or 50 km/h. One-way streets had a minor effect, with a significant negative association at 30 km/h but only a marginal effect at 50 km/h, while lane markings did not show significant associations with safety perception across any speed limit category. These results indicate that drivers' safety perceptions are influenced by different road characteristics depending on the speed environment, with bike lanes and road surface playing crucial roles in shaping perceived safety at higher speeds, whereas factors like lane width and one-way configurations have more relevance in lower-speed contexts.

4.2.4. Associations between road characteristics and credibility ratings

The final section of this sub-chapter, which examined the associations between road characteristics and people's perceptions regarding speed limit suitability and safety, and to a larger extent the final section of the entire results chapter, concerns what is arguably the most important and the most consequential set of findings that can be derived from this entire study: The influence of road characteristics on speed limit credibility perception. The results presented in this section directly relates to the central theme surrounding the whole research and is therefore the crux of the research matter. By combining previous findings on road characteristic effects on speed limit and safety perceptions, together with the findings presented in this section, an overarching conclusion can be drawn regarding how drivers' perceptions of the road environment can impact and lend credibility to speed limits, formally answering the problem given by the third sub-question and the main research question as a whole.

To briefly recap, speed limit credibility refers to the extent to which drivers perceive the posted speed limit as appropriate given the design and features of the road. Understanding the associations between road design characteristics and the perceived credibility of speed limits is crucial for evaluating whether specific road characteristics contribute to driver compliance with speed limits or, conversely, create discrepancies between the intended and perceived safe driving speeds. The analysis explores how factors such as lane width, the presence of lane markings, road surface type, and different bike lane configurations, among others, influence drivers' perceptions of speed limit credibility across different speed limit categories. By identifying significant predictors and their effects, these findings provide insights into how road design can be optimized to enhance speed limit compliance and overall road safety.

In addition to speed limit perception and perceived safety, survey respondents were also asked to rate the credibility of a given speed limit for each of the eight road design scenarios. The rating is also based on a Likert scale from 1 (not credible at all) to 5 (very credible), and respondents had to give a rating according to a 30 km/h speed limit scenario and a 50 km/h speed limit scenario. These scenarios are irrespective of the actual speed limits posted for each of the road scenarios presented, and comparisons can therefore be made between 30 km/h and 50 km/h speed limit credibility ratings, in order to assess the extent of which certain characteristics may contribute to an improvement in credibility of one speed limit scenario and a reduction in the other. As was done previously in the analyses of speed limit perception and safety perception, ordinal logistic regression was used to determine associations between road characteristics and speed limit credibility perception (see Appendix H, Tables H.6 and H.7 for full SPSS outputs).

The results of the ordinal logistic regression analysis indicate several significant associations between road characteristics and the perceived credibility of a 30 km/h speed limit. Road surface type appears to have a notable effect, as roads with asphalt surfaces are significantly less likely to be perceived as credible for a 30 km/h speed limit, with an associated 85.6% decrease in the odds of selecting a higher credibility category. The presence of bike lanes also has a strong influence on credibility perceptions. Roads without bike lanes are significantly more likely to be perceived as credible for a 30 km/h speed limit, with a 29-fold increase in the odds of a higher credibility rating. Similarly, roads with mixed gutter/separated bike lanes and bicycle gutters also exhibit increased credibility perceptions, though their significance levels are slightly higher. In contrast, lane width, one-way street status, and lane markings do not show statistically significant effects on speed limit credibility, suggesting that these factors may not play a major role in shaping perceptions.

Table 4.8. Logistic regression results of 30 km/h speed limit credibility perception.

Road Characteristic	B Coefficient	Odds Ratio	p-value
Lane width	-0.812	0.444	0.081
One-way street (no)	-0.207	0.813	0.559
Lane markings (no)	0.046	1.047	0.941
Road surface (asphalt)	-1.935	0.144	0.028 (significant)
Bike lanes (none)	3.371	29.070	0.029 (significant)
Bike lanes (gutter)	2.371	10.710	0.080
Bike lanes (mixed gutter/separated)	3.062	21.357	0.053

Building on the findings for 30 km/h speed limit credibility perception, the results for roads with a 50 km/h speed limit indicate notable effects of road characteristics on perceived credibility. Road surface type was found to have a significant impact, with asphalt roads being associated with a 501.95% increase in the odds of perceiving the 50 km/h speed limit as more credible. The presence of bike lanes also played a crucial role, as roads without bike lanes were associated with a 93.63% decrease in the odds of a higher perceived credibility category. Although the effects of bicycle gutters and mixed gutter/separated bike lanes did not reach conventional significance levels, they showed trends toward reduced perceived credibility, with decreases of approximately 80.23% and 90.50%, respectively. Other factors, such as lane width, the presence of lane markings, and one-way street configuration, did not show significant associations with perceived credibility. These results highlight the role of road design elements in shaping driver perceptions of speed limit credibility at higher speed roads, reinforcing the influence of surface type and bike lane presence.

Table 4.9. Logistic regression results of 50 km/h speed limit credibility perception.

Road Characteristic	B Coefficient	Odds Ratio	p-value
Lane width	0.107	1.113	0.787
One-way street (no)	-0.435	0.647	0.143
Lane markings (no)	-0.443	0.642	0.432
Road surface (asphalt)	1.795	6.018	0.017 (significant)
Bike lanes (none)	-2.753	0.064	0.042 (significant)
Bike lanes (gutter)	-1.621	0.198	0.165
Bike lanes (mixed gutter/separated)	-2.354	0.095	0.090

Comparing the results for 30 km/h and 50 km/h speed limit credibility perceptions, several key differences emerge in how road characteristics influence perceived credibility. Road surface played a significant role at both speed limits but in opposite directions; while asphalt roads were associated with a lower credibility perception for 30 km/h roads, they significantly increased the odds of perceiving the 50 km/h speed limit as credible. This suggests that drivers may associate asphalt roads with higher-speed environments, making lower speed limits feel less appropriate. Similarly, the presence of bike lanes was influential in both contexts, but again with differing effects. Roads without bike lanes significantly reduced perceived credibility for a 50 km/h speed limit, whereas for 30 km/h roads, the absence of bike lanes substantially increased perceived credibility. This contrast suggests that the presence of bike lanes may serve as a visual cue reinforcing lower speed limits, while their absence on higher-speed roads challenges the legitimacy of a 50 km/h limit. Other factors, such as lane width and lane markings, showed no significant influence in either model, while the presence of one-way streets was only marginally associated with credibility perceptions for 30 km/h roads. These findings highlight how driver expectations of appropriate speed limits are closely tied to specific road design features, varying based on the intended speed regime.

5. Discussion

5.1. Theoretical contribution

This study attempted to bridge research gaps in the fields of road safety and traffic engineering, and in particular, it aimed to contribute to the already limited body of research surrounding driving behaviour and the role of road design in lower-speed urban environments. Traditionally, road safety research tend to focus on rural or suburban environments, with a particular focus on highway safety and speed management on rural distributor roads. The bulk of these studies emphasize the importance of speed management and accident prevention in a higher-speed context, as the risk of fatal crashes on high-speed roads are significantly higher than in a lower-speed context, such as in an urban area (Lu, Qurashi and Antoniou, 2023; Schaefer, Figliozzi and Unnikrishnan, 2022; Son et al., 2022; Zhai et al., 2022). These studies therefore primarily focus on the safety of the driver and the prevention of vehicle-to-vehicle collisions. While this also holds true for the context of this thesis, the focus is more on the safety of other road users, such as cyclists and pedestrians, especially given that the scope of the thesis is on urban environments which have much higher volumes of pedestrians and cyclists as opposed to rural areas. The insights gained in this study contribute to a better theoretical understanding of how road design can influence driving behaviour and improve road safety in an urban context, by incorporating the complexities of hierarchical urban road networks and human-centric infrastructure design elements that tailor to the needs of various road users, with the incorporation of such complexities often lacking in other road safety studies.

Additionally, and more specifically, the focus on 30 km/h roads has been theoretically unexplored in previous studies. The relatively recent introduction of GOW30 as a new road category in the Netherlands has brought about some uncertainty regarding how drivers would behave on roads that have transitioned from a 50 km/h speed limit to a 30 km/h one. As such, there is a lack of data regarding the effects of this transition on vehicle speeds and driving behaviour, and moreover, the effectiveness of various road design interventions on ensuring compliance with the new speed limit. This thesis attempted to close that theoretical gap by investigating vehicle speeds and driving behaviour on existing 30 km/h and 50 km/h roads, and how certain road design features, particularly with those used for 30 km/h roads, can be applied to 50 km/h roads in order to reduce vehicle speeds in the event of a speed limit reduction on those roads.

The most consequential theoretical contribution that this study provides is the focus on speed limit credibility. Most studies on speed limits primarily focus on compliance or risk perception, which typically results in the separation of objectively measurable factors of road safety (such as speed limit compliance and accident rates) and the more subjective and psychological aspects of road safety (such as risk perception and drivers' cognition) (Ambros et al., 2021; Charlton & Starkey, 2017; Yao et al., 2019a; 2019b; 2020a; 2020b). While examining the two aspects separately may be useful in understanding specific contexts of road safety, they do not necessarily provide a holistic overview of the underlying processes and factors that contribute to safer roads in general. The focus on speed limit credibility attempted to address those shortcomings by combining objective and subjective aspects of road safety to give a more holistic overview and to better understand the underlying factors of driving behaviour and speed limit compliance, specifically by examining road design and vehicle speeds (objective factors) and their relationships with risk perception and speed limit credibility perception (subjective factors). These relationships are addressed in the conceptual framework shown in Figure 4.3, which shows risk perception as the linking variable between road design and speed limit credibility.

5.2. Practical implications

The outcome of this study outlines several clear design and infrastructure policy implications for municipalities and road authorities throughout the Netherlands (and in other countries that aim to adopt a Vision Zero approach). For the successful implementation of GOW30, it is important to make sure that the design of a road or street visually and structurally aligns with the given speed limit. This helps ensure that drivers are more likely to comply with the speed limit and would reduce reliance on enforcement techniques alone. For 30 km/h roads in particular, the incorporation of "self-explaining" road design principles can help guide drivers to adopt safe speeds in an intuitive manner. Such design principles include lane narrowing, the use of brick road surfaces and the integration of bicycle and motor traffic (absence of bike lanes), all of which have been found to contribute to lower vehicle speeds and improved credibility perceptions of 30 km/h speed limits. Wide lanes, asphalt surfaces and bike lane separation would end up having an opposite effect, so municipalities would need to pay particular attention to these types of roads and redesign them accordingly if they plan on imposing a 30 km/h speed limit on these roads.

A possible point of contention for policy-makers and traffic engineers when it comes to road (re)design, especially with regard to GOW30, is the need to balance traffic flow and safety. As discussed in Appendix A.5, the main function of GOW is traffic flow (i.e. travelling from A to B as quickly and as efficiently as possible). However, the introduction of a 30 km/h speed limit on roads with a GOW function would seem counter-intuitive and may end up impeding traffic flow. This poses a challenge for policy-makers and engineers as, on the one hand, they want to ensure that traffic flows as smoothly and as efficiently as possible within the city, while on the other hand they want to prioritise road safety and minimise accidents between vehicles and with other road users. The design of a road plays a big role in striking this delicate balance between traffic flow and safety, as they would have to be designed in such a way that would allow traffic to flow freely with minimal hindrance, while at the same time making sure that drivers adopt safe speeds to protect themselves as well as other road users. Because this thesis primarily focused on improving road safety and speed limit credibility through road design, the traffic flow aspect and the challenges it poses for GOW30 implementation was not thoroughly explored. However, the outcomes of this study may still be useful to policy-makers and traffic engineers for them to determine the most optimal road configuration according to their priorities. For example, a road design that takes into account of the balance between traffic flow and safety may include lane narrowing and brick road surfaces to induce slower driving, but may also include separated bike lanes to improve traffic flow. Further research would need to be conducted in order to determine this optimal configuration and its effects on traffic flow and road safety.

5.3. Research limitations and future recommendations

The scope of this study is comprehensive in nature and aims to provide a holistic outlook on the relationship between road design and speed limit credibility. However, due to this comprehensive outlook, as well as the limited body of existing research surrounding speed limit credibility, some limitations apply to the research methodology which have resulted in some generalisations and assumptions regarding the real effects of various road design elements on speed limit credibility. One of these limitations, which has been mentioned in the previous section, is the lack of understanding of how different road configurations would impact traffic flow under a 30 km/h speed limit regime. This study mainly focused on optimising road design for safety rather than traffic flow, which is typically the main reason for setting a 30 km/h speed limit. Under the context of GOW30 however, traffic flow holds equal importance with safety, so the impact of a 30 km/h road design on traffic flow would need to be further investigated in order to ensure that GOW30 can be implemented smoothly and an optimal road design can be conceptualised that balances the need for traffic flow and safety.

Another limitation of this study is the lack of before-and-after data regarding vehicle speeds driven on roads that have already transitioned from GOW50 to GOW30. This study heavily relied on speed data from existing 50 km/h and 30 km/h roads (regardless of whether or not those roads have transitioned from GOW50 to GOW30), and conclusions were based on speed comparisons between different roads with different speed limits and road designs, rather than on the same road that have changed from a 50 km/h speed limit to a 30 km/h one. As a result, generalisations had to be made about the effects of a speed limit transition on vehicle speeds, as there is no direct evidence of what these effects are on roads that have undergone this transition. Furthermore, the data from Telraam was only limited to select road segments across a few of the major cities and towns in the Netherlands, so the case selection of road segments used in the analysis of vehicle speeds was only limited to what was available in the Telraam database. Most of these road segments only recorded speed data over a short period of time (usually 2 to 3 years, due to Telraam being a relatively young company and the reliance on community members to utilise their services), and such a time frame is not long enough to measure any real differences in vehicle speeds on roads that have undergone a road design overhaul (as many of the Telraam devices used to measure vehicle speeds were installed after a road had been redesigned). Additionally, the data itself may not be entirely accurate due to the devices being susceptible to weather conditions and the possibility that these devices may not be optimally placed to make precise measurements. Therefore, in order to obtain more reliable speed data and to more accurately determine the true effects of the GOW30 transition, it is recommended that future studies into this subject collect speed data on-site (e.g. with the use of speed guns instead of relying on privately-owned Telraam devices) on roads that are scheduled to have a speed limit reduction and/or a road redesign, so then it would be possible to make speed comparisons before and after the speed limit reduction/road redesign.

6. Conclusions

The purpose of this study was to investigate the effectiveness of various road characteristics on enhancing the credibility of a 30 km/h urban speed limit. As cities in the Netherlands begin to transition from a 50 km/h speed limit to a 30 km/h one for most of their urban distributor roads (i.e. transitioning from GOW50 to GOW30), it is imperative to understand how road design plays a role in influencing driving speeds, and the insights gained from this analysis can then be utilised to implement road design strategies that aims to ensure that drivers comply with the new 30 km/h urban speed limit. The successful implementation of GOW30 predominantly relies on whether or not a 30 km/h speed limit is considered credible given the design of the road that the limit is imposed on, as simply changing the speed limit from 50 km/h to 30 km/h would not be enough to encourage slower and safer driving speeds. Therefore, the main objective of this study is to determine which set of road characteristic variations can meaningfully lead to a reduction in vehicle speeds in order to legitimise and improve the credibility of GOW30.

As such, the main research question was formulated as follows: "*What road design characteristics are the most effective for bolstering the credibility of GOW30?".* This was supplemented by three sub-questions: 1) "*Based on literature, what factors influence the credibility of a speed limit?";* 2) *"What are the effects of various road design characteristics on actual speeds being driven on urban roads?";* and 3) *"What are the effects of various road design characteristics on drivers' perceptions towards speed limit credibility and safety?".* The main conclusion that can be drawn from the first sub-question is derived from the literature review and the conceptual framework (Figure 4.3), which found that drivers' perception of road risk is a predominant factor of speed limit credibility. Factors affecting risk perception include the road environment (which includes road design, the official speed limit and the surrounding environmental context) and driving behaviour, thereby encompassing both the physical (objective) and the psychological (subjective) attributes relating to risk perception. These two attributes of risk perception together determine how drivers perceive the speed limit (i.e. whether they think the speed limit is too high, too low, or appropriate given the level of risk perceived by drivers), and that perception ultimately determines the credibility of the speed limit.

As for the second sub-question, the road characteristics that were found to have the most significant effects on vehicle speeds were lane width, the presence of lane markings, road surface type and the presence and nature of bike lanes. Characteristics that resulted in higher vehicle speeds include wider lanes, the absence of lane markings, the use of asphalt surfaces and the presence of bicycle gutter lanes. Narrower lanes, present lane markings, brick surfaces and the absence of bike lanes all contributed to vehicle speed reductions. There were some slight differences in these effects between 30 km/h roads and 50 km/h roads (e.g. a negative relationship between lane width and vehicle speed was found on 30 km/h roads, but not on 50 km/h roads), however these effects were not significant enough to make definitive conclusions about the influence of road design variations on vehicle speeds per speed limit category.

And finally, the analysis regarding the third sub-question revealed that road surface and the presence of bike lanes showed the most significant effects on drivers' perceptions of speed limit credibility and safety. These effects were consistent throughout the analysis, with significant effects of these characteristics found on speed limit perception, safety perception and speed limit credibility perception. Asphalt surfaces contributed to improvements in safety and credibility perceptions on 50 km/h roads, but the opposite was found for 30 km/h. Conversely, brick surfaces contributed to improved safety and credibility perceptions on 30 km/h roads, but not for 50 km/h roads. As for bike lanes, the absence of them had the most significant impact on perceptions out of all the bike lane configurations. They contributed to improved safety and credibility perceptions on 30 km/h roads, while significantly reducing these perceptions on 50 km/h roads. Other bike lane configurations showed limited effects, with bicycle gutters and mixed configurations only contributing to negative safety perceptions on 50 km/h roads.

The main conclusion that can be drawn from the entire analysis and therefore providing an answer to the main research question, is that road surface type and the presence (or absence) of bike lanes appear to be the most effective road design characteristics in enhancing the credibility of GOW30. These characteristics showed consistent significant effects on both vehicle speeds and drivers' credibility and safety perceptions. In particular, the use of brick surfaces and the absence of bike lanes contributed to vehicle speed reductions and improved credibility and safety perceptions on 30 km/h roads, thereby the inclusion of these characteristics in road design would greatly benefit the credibility of GOW30. Other characteristics, such as narrower lanes and the use of lane markings, would also positively contribute to GOW30 credibility, and may be included in road design to further supplement the positive effects of brick surfaces and absent bike lanes. These findings ultimately have implications on traffic policy and strategic road design for municipalities throughout the Netherlands as they transition from GOW50 to GOW30, as was already discussed in the previous chapter.

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Appendix A: Theoretical foundations of road safety

Appendix A.1: Strategies for managing speed

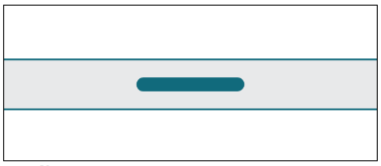
Speed management is a fundamental aspect of transportation planning and safety that involves regulating the speed of vehicles on roads and highways to ensure efficient traffic flow and reduce the risk of accidents. It encompasses various strategies and techniques aimed at influencing driver behaviour and controlling vehicle speeds within safe limits. The most common method for managing driving speeds is through the establishment of legal speed limits, which are typically set by local road authorities and therefore provides road users a basic indicator of the maximum speed allowed on a given stretch of road under the law (European Transport Safety Council, 2010). The determination of a speed limit is based on a variety of considerations, such as the design of a road, its intended function, traffic volume, traffic composition, and the surrounding environment (European Transport Safety Council, 2019; Sadeghi-Bazargani and Saadati, 2016; SWOV, 2021). The ways in which speed limits are determined and justified differs from country to country (see Appendix A.2) and are typically upheld by enforcement techniques that are meant to discourage speeding behaviour and promote compliance with speed regulations. Examples of such techniques include the utilization of radar guns, speed cameras and police patrols, and consequences for disobeying the speed limit may include receiving a fine and, in extreme cases, the suspension of one's driver's license and possible jail time.

Another common strategy to manage driving speeds is through the implementation of engineering measures. Engineering measures to manage speed encompass a range of strategies and interventions aimed at influencing driving behaviour and reducing vehicle speeds in specific areas. These measures often involve comprehensive plans to modify the design and layout of road infrastructure to create environments that encourage drivers to travel at safe speeds (Institute of Transportation Engineers, n.d.). The Institute of Transportation Engineers, based in the United States, defines a couple of important concepts which are central to the implementation of engineering measures, including:

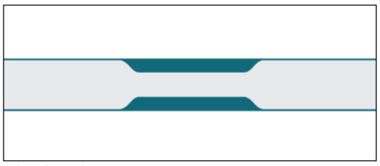
Traffic Calming – a combination of physical infrastructural measures meant to influence drivers' behaviour by inducing slower speeds and improve conditions for all road users.

Self-enforcing road – sometimes known as a "self-explaining road", it is a road that encourages drivers to select driving speeds consistent with the speed limit. As the name suggests, these roads are designed in such a way so that the speed limit feels natural and intuitive, and therefore drivers are more inclined to drive appropriate speeds and also reduces the need for additional enforcement techniques.

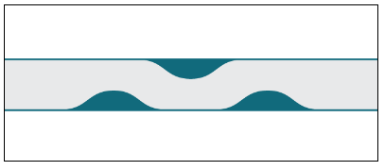
Traffic calming can be categorised into measures that involve "horizontal deflection", "vertical deflection" and street width reduction. Horizontal deflection includes measures that "hinders the ability of a motorist to drive in a straight line by creating a horizontal shift in the roadway" (Institute of Transportation Engineers, n.d.). This shift forces drivers to reduce their speed in order to comfortably and safely navigate the measure. Examples of horizontal deflection measures include, but not limited to, lateral shifts (lane shifts), chicanes, and roundabouts. Vertical deflection, on the other hand, are measures that "creates a change in the height of the roadway that forces a motorist to slow down in order to maintain an acceptable level of comfort" (Institute of Transportation Engineers, n.d.). Examples of vertical deflection measures include, but not limited to, speed humps, raised pedestrian crossings, and raised intersections. The third category of traffic calming measures, street width reduction, is rather self-explanatory in nature, as it involves the narrowing of a road lane through various means. This aims to result in drivers reducing their speed in order to maintain an acceptable level of comfort and safety. Additionally, it can also reduce the distance a pedestrian would need to walk in order to cross a street, thereby minimising conflicts between pedestrians and motor vehicles (Institute of Transportation Engineers, n.d.). Examples of street width reduction measures include, but not limited to, physical lane narrowing through road markings or curb extensions, medians or pedestrian refuge islands, on-street parking, and tree linings. Figures A.1 and A.2 shows visualisations of the layouts of various traffic calming measures, along with their descriptions (taken from the Urban Street Design Guide developed by the National Association of City Transportation Officials, based in the USA).



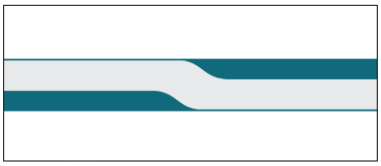
Median
Medians create a pinchpoint for traffic in the center of the roadway and can reduce pedestrian crossing distances.



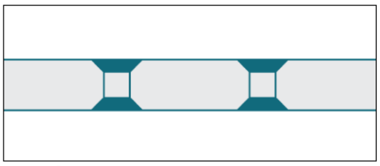
Pinchpoint
Chokers or pinchpoints restrict motorists from operating at high speeds on local streets and significantly expand the sidewalk realm for pedestrians.



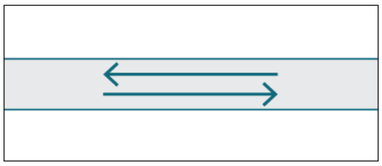
Chicane
Chicanes slow drivers by alternating parking or curb extensions along the corridor.



Lane Shift
A lane shift horizontally deflects a vehicle and may be designed with striping, curb extensions, or parking.



Speed Hump
Speed humps vertically deflect vehicles and may be combined with a midblock crosswalk.



2-Way Street
2-way streets, especially those with narrower profiles, encourage motorists to be more cautious and wary of oncoming traffic.

Figure A.1. Examples of traffic calming measures (National Association of City Transportation Officials, n.d.).

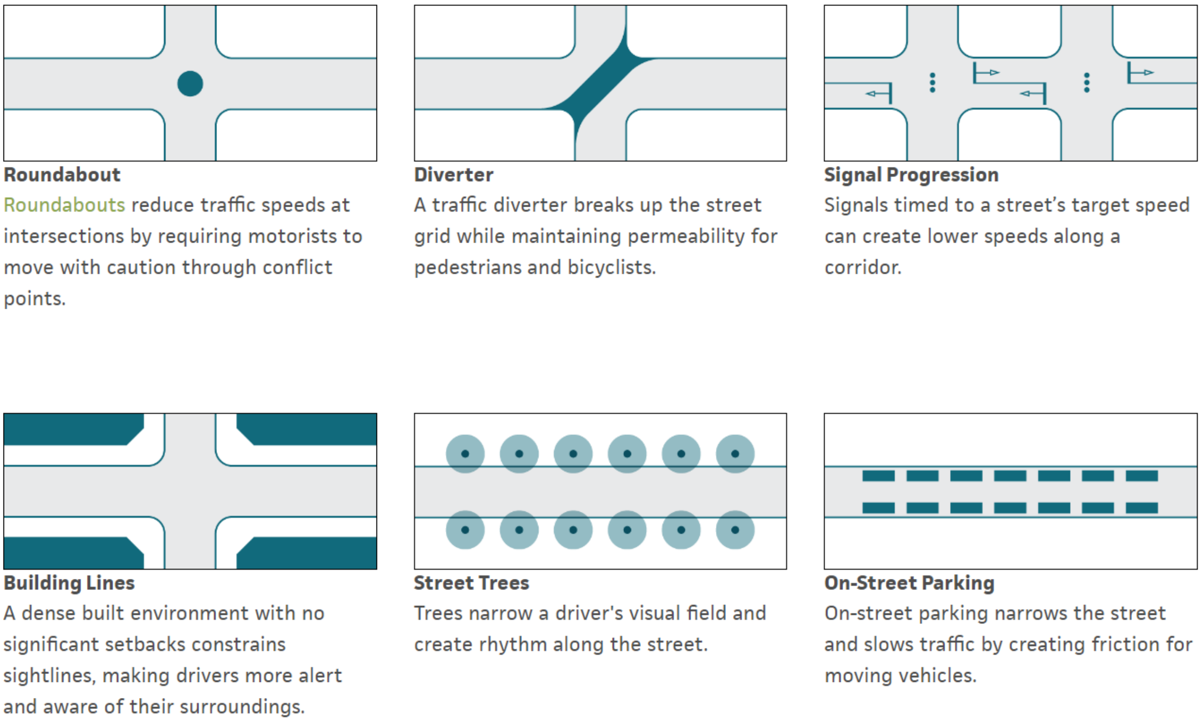


Figure A.2. Examples of traffic calming measures (cont.) (National Association of City Transportation Officials, n.d.).

Other strategies utilised for speed management purposes may include, but are not limited to:

- **Education and awareness** - conducting public awareness campaigns and educational initiatives to inform drivers about the importance of speed management and the risks associated with excessive speeding. These efforts aim to promote responsible driving behaviour and encourage drivers to comply with speed limits.
- **Technological solutions** - leveraging advancements in vehicle technology and intelligent transportation systems to support speed management efforts. This includes the use of speed-limiting technology such as Intelligent Speed Assistance (ISA), adaptive cruise control systems, and vehicle-to-infrastructure communication to assist drivers in maintaining safe speeds.

Appendix A.2: Conventional methods for setting speed limits

Speed limits are typically set through a combination of engineering, legal and safety considerations. The process of establishing speed limits involves a close examination of various factors to determine the appropriate maximum speed for a particular road segment. In practice, there are multiple approaches to setting speed limits and these approaches tend to differ between countries and road authorities.

One of the more common methods for setting speed limits, particularly in North America, is through an engineering approach that determines speed limits based on the "85th percentile speed". The 85th percentile speed is a commonly used metric in traffic engineering and road safety that refers to the speed at or below which 85% of vehicles are traveling on a given road segment under free-flow conditions (Federal Highway Administration, 2012). This speed is determined through field studies that collect data on vehicle speeds using radar guns, speed cameras, or other monitoring devices. These studies are conducted over a representative period of time to capture a sufficient sample of vehicle speeds. Once the speed data is collected, it is analysed to identify the speed at which 85% of vehicles are traveling at or below. This speed represents the typical or prevailing speed of traffic under normal driving conditions, excluding outliers such as excessive speeding or those traveling at very low speeds, and thus the speed limit is set at or near this 85th percentile speed (usually in 5 mph increments) as a reasonable speed limit that matches the free-flow conditions on a given road segment (Federal Highway Administration, 2012).

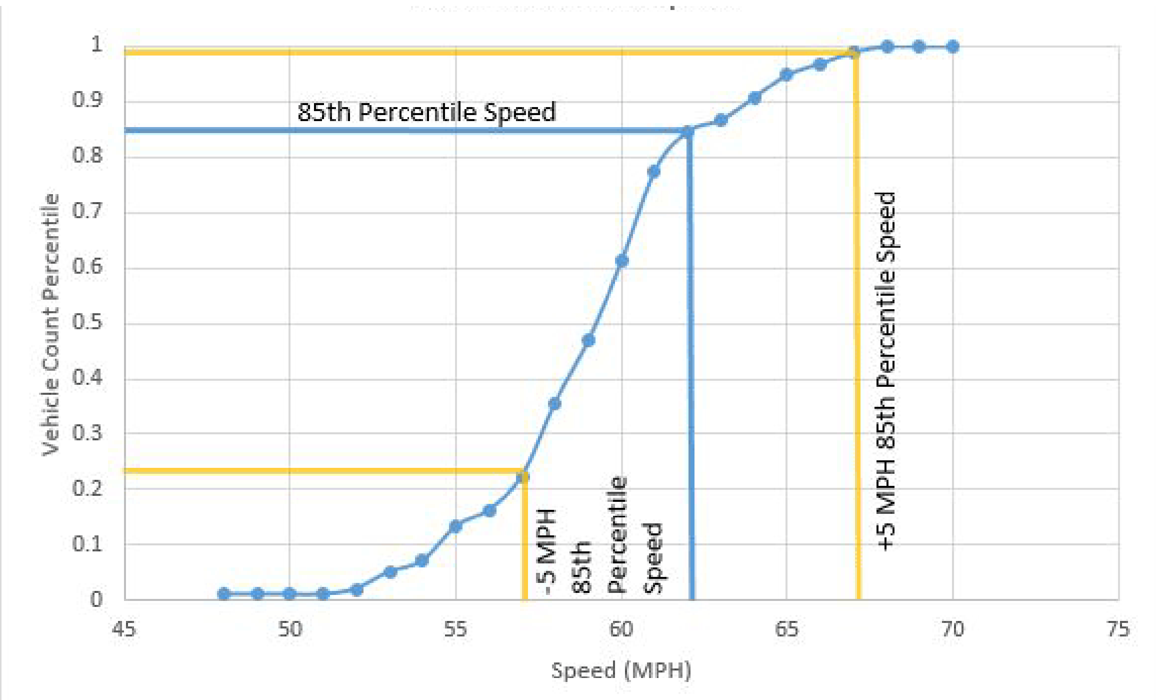


Figure A.3. 85th percentile speed relative to vehicle count (Institute of Transportation Engineers, n.d.).

The rationale behind using the 85th percentile speed as a metric to set speed limits is that it reflects the collective behaviour of the majority of drivers and is considered a reasonable and safe speed for the given road conditions (Federal Highway Administration, 2012). Furthermore, it was also used as a safety metric: Research has shown that drivers travelling at or around one standard deviation above the 85th percentile speed resulted in the lowest crash risk for drivers, while the crash risk increases significantly for drivers travelling around two standard deviations or more above or below the 85th percentile speed (Federal Highway Administration, 2012). However, it is important to note that this research is dated and may not be valid by today's standards. While the 85th percentile speed can be a useful tool for setting speed limits, it is important to consider other factors such as road geometry, road function, traffic volume and crash history when determining appropriate speed limits. Safety goals and concerns should be a leading priority when it comes to tackling issues related to speed management, in which the Safe System approach attempts to address in the following section.

Appendix A.3: Safe System approach

The Safe System approach to speed management, also known as “Vision Zero”, is a holistic and comprehensive framework for addressing road safety that prioritizes the prevention of road traffic deaths and serious injuries. It emphasizes the creation of forgiving road environments and the reduction of the risk of crashes through a combination of interventions targeting road users, vehicles, and the road infrastructure. Speed management is a central component of the Safe System approach, as speed plays a critical role in determining the severity of crashes and their likelihood of occurring (World Health Organization, 2023).

Unlike conventional approaches to speed management, the Safe System approach acknowledges that road transport is a complex system with layers of interaction between humans, vehicles and road infrastructure (World Health Organization, 2023). This implies that road safety is a shared responsibility among the stakeholders involved, including drivers, car manufacturers and road authorities. The leading principle behind the Safe System approach is that there is no acceptable number of road fatalities and serious injuries, and therefore road deaths and serious injuries must be completely eradicated (hence the name “Vision Zero”, alluding to the fact that this approach strives for zero deaths and serious injuries) (European Commission, 2022; U.S. Department of Transportation, 2022). This approach also recognises that humans are prone to errors and mistakes, and therefore the road system should accommodate for it. This means that the road system should be forgiving when an accident does occur, such that system redundancies are put in place and impact forces are minimised to survivable levels (European Commission, 2022). This principle is best conceptualised by using a Swiss Cheese model, as shown in Figure A.4.

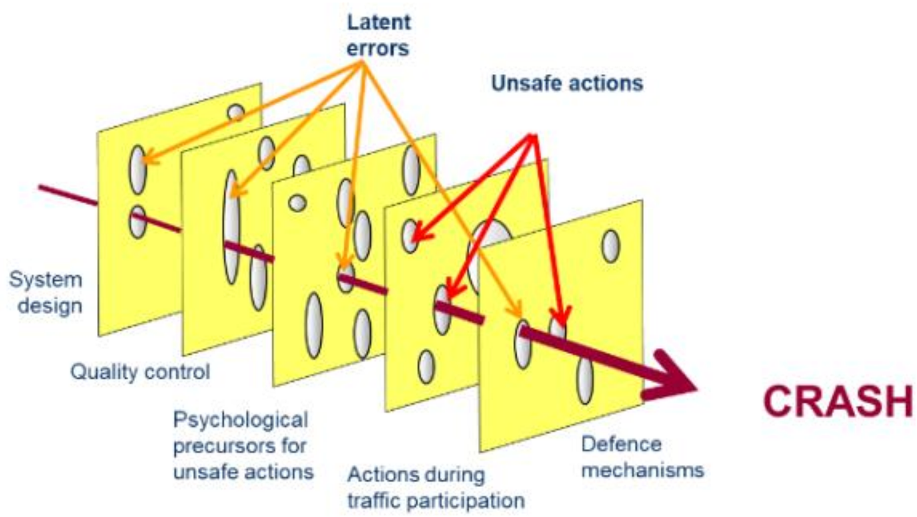


Figure A.4. Swiss Cheese model of a Safe System (European Commission, 2022).

The Swiss Cheese model shows that if a failure (or a latent error) occurs in one part of the system, then the redundancies and defence mechanisms put in place should prevent it from leading to a serious accident, as long as these latent errors and unsafe actions made by road users do not coincide (represented by the “holes” in the cheese slices). Even if a crash does occur, impact forces are minimised to levels that are within human tolerance so that death and serious injury can be prevented (World Health Organization, 2023). The aspect of human vulnerability is also a central component of the Safe System approach, so road systems should be designed in such a way that these vulnerabilities are taken into account. One way of addressing these vulnerabilities is through the implementation of safe speed limits, shown in Table A.1.

Table A.1. Safe speed limits according to the Safe System approach (World Health Organization, 2023).

Type of road/road section	Safe System speed
Roads/road sections with possible crashes between cars and vulnerable road users	Max. 30 km/h
Roads/road sections with intersections with possible side-on crashes between cars	Max. 50 km/h
Roads/road sections with possible frontal (head-on) crashes between cars	Max. 70 km/h
Roads/road sections with no likelihood of side-on or frontal crashes between cars	Max. 100 km/h

Overall, the Safe System approach can be summarized by the following points (extracted from the European Commission's Road Safety Thematic Report on the Safe System approach (2022)):

- *"People make errors, which is accommodated by system design that supports safe road user behaviour to prevent crashes."*
- *"As people are vulnerable, the system design is forgiving and prevents exposure to large crash impacts to reduce the probability of severe injury."*
- *"System providers share the responsibility for Safe System design."*
- *"All elements of the system are strengthened in combination to multiply their effects and to ensure safety when one of the elements fails."*

In addition, five road safety pillars have been identified to ensure that Safe System objectives can be achieved (European Commission, 2022; U.S. Department of Transportation, 2022):

- Safe speeds
- Safe infrastructure
- Safe vehicles
- Safe road user behaviour
- High quality post-crash care

The combination of these key components and objectives to improve road safety results in stark contrasts between the Safe System approach and traditional road safety approaches, especially in terms of the underlying goal, accident mitigation and prevention, and who ultimately bears the burden of responsibility when a crash does occur. These differences are summarised in Table A.2.

Table A.2. Differences between a traditional road safety approach and the Safe System approach (European Commission, 2022).

Viewpoints	Traditional road safety policy	Safe System Approach
What is the problem?	Try to prevent crashes.	Prevent crashes from resulting in fatal and serious casualties.
What is the appropri-ate goal?	Reduce the number of fatalities and serious injuries.	Zero fatalities and serious inju-ries.
What are the major planning approaches?	Reactive to incidents. Incremen-tal approaches to reduce the problem.	Proactively target and treat risk. Systematic approach to build a safe road system.
What causes the problem?	Non-compliant road users.	People make mistakes and peo-ple are physically vulnerable. Var-ying quality and design of infra-structure and operating speeds provide inconsistent guidance to users about what is safe use be-haviour.
Who is ultimately responsible	Individual road users.	Shared responsibility by individu-als with system designers.
How does the system work?	Is composed of isolated inter-ventions.	Different elements of a Safe Sys-tem are combined to produce a summary effect greater than the sum of the individual treatments – so that if one part of the system fails, other parts provide protec-tion (redundancy).

The Safe System approach has been adopted by many countries worldwide as well as some major international organisations such as the European Union and the World Health Organization (European Commission, 2022; World Health Organization, 2023). Some of the earliest adopters of the Safe System approach include the Netherlands and Sweden, which have adopted their respective versions of the Safe System approach in the 1990s and have seen a reduction in road fatalities by 30 to 50 percent as a result (European Commission, 2022). The Dutch version of the Safe System approach, known as Sustainable Safety (*Duurzaam Veiligheid* in Dutch), is discussed in more detail in the following section.

Overall, the Safe System approach to speed management recognizes that road safety is a shared responsibility that requires a coordinated effort from government agencies, road users, vehicle manufacturers, and other stakeholders. By prioritizing the prevention of serious injuries and fatalities and focusing on creating forgiving road environments, the Safe System approach aims to create safer, more sustainable transportation systems for all road users.

Figure A.5. Safe System approach (World Health Organization, 2023).

Appendix A.4: Sustainable Safety

The Sustainable Safety vision to road safety, originally pioneered in the Netherlands, was a first-of-its-kind implementation of the Safe System approach in practice. As such, it is a proactive and systematic framework designed to maximise road safety by preventing severe road traffic injuries and fatalities on Dutch roads as much as possible. Following the principles of the Safe System approach, the vision of Sustainable Safety is grounded in what is known as the "human dimension": The understanding that human beings are vulnerable and are prone to errors, and that road systems should be designed to minimise the consequences of these errors (SWOV, 2019). In addition, the vision also acknowledges that due to varying mobility demands among different groups in society, as well as the varying demographic characteristics of road users (particularly children and the elderly), the road system must be accommodating and protective of users travelling with transport modes that are inherently less safe (such as bicycles) and users that are more vulnerable to road injuries. To address these road safety concerns, three main approaches are distinguished (SWOV, 2018):

- **Eliminating:** Dangerous situations are made physically impossible so that people do not find themselves in such situations.

- **Minimizing:** The number of dangerous situations are limited and certain modes of road transport are made unattractive to limit people's exposure to risks.

- **Mitigating:** When people are exposed to risks, their consequences should be mitigated as much as possible by taking appropriate mitigating measures.

Under the Sustainable Safety approach, the Netherlands has implemented a range of measures to create a safer road environment. These measures include the categorization of roads into distinct types with appropriate speed limits and design features based on their intended functions, the separation of different types of traffic (e.g., motor vehicles, bicycles, and pedestrians) to reduce conflicts, and the use of infrastructure that inherently reduces the risk of serious accidents, such as roundabouts and traffic calming measures in urban areas. The emphasis is on creating a self-explaining and forgiving road environment, where road users are guided intuitively to behave safely, and the road system itself is designed to absorb and reduce the impact of crashes. This comprehensive and preventive approach has significantly contributed to the Netherlands' reputation as one of the safest countries in the world for road traffic (Wegman et al., 2005).

The vision itself was developed in the early 1990s as a response to the need for a more systematic and proactive approach to road safety. The concept was born out of growing concern over road traffic injuries and fatalities and the realization that traditional methods of addressing road safety were insufficient. The vision was first conceptualised in 1992 based on research conducted by researchers from the Dutch Institute for Road Safety Research (SWOV), which laid the groundwork for the implementation of small demonstration projects around the country in 1995 by the Ministry of Infrastructure and Water Management (Wegman, Aarts and van der Knaap, 2022; SWOV, 2018; 2019). Following the success of these small-scale pilot projects, the "Start-up Programme Sustainable Safety" was formally adopted as an agreement between the national government and local authorities in 1997. This marked the first phase of a nationwide implementation of the Sustainable Safety vision between 1997 and 2002 (SWOV, 2019; Wegman et al., 2005).

During the first phase of the vision's implementation, three key principles of road design were introduced (Wegman, Aarts and van der Knaap, 2022; Wegman et al., 2005), namely:

- **Functionality:** Roads are categorised based on their intended use or function. This introduces a clear hierarchy in the road network and therefore aims to prevent unintended road use. Defined road categories include through roads, distributor roads and access roads (see Section 3.2 for more details).

- **Homogeneity:** This principle ensures that vehicles of similar mass and speed travel in the same directions to minimize the risk of severe crashes. For example, heavy trucks are separated from lighter vehicles and pedestrians or cyclists are provided with their own lanes or paths.

- **Predictability:** Road environments are designed to be predictable and simple, allowing users to easily understand what is expected of them. Consistent road designs, clear signage, and uniform traffic rules help reduce confusion and prevent errors.

The Start-up Programme also resulted in a package of six "action plans" that were targeted towards changing the road infrastructure as well as any legislation that regulated the use of it. These action plans included the functional categorisation of all roads in the Netherlands, the expansion of 30 km/h zones in urban areas and 60 km/h zones in rural areas, assigning priority on intersections and roundabouts, and removing mopeds from bicycle paths and redirecting them onto the carriageway when safe to do so (SWOV, 2019; Wegman et al., 2005).

The first revision of the Sustainable Safety approach in 2005 signified the beginning of the second phase of its implementation. Building on the initial successes, the second phase aimed to refine and expand the approach. During this period, road authorities continued to implement measures outlined in the Start-up Programme while also adapting them based on insights gained from the first stage of implementation as well as aligning the vision more with social developments at the time (Wegman, Aarts and van der Knaap, 2022; SWOV, 2018; 2019). At this point, the vision was no longer laid down in separate agreements but were integrated into general policy plans (SWOV, 2019). The revised approach was laid out in the report "Advancing Sustainable Safety" published in 2005 and had an outlook until 2020.

On top of the three key principles mentioned previously, two new principles were introduced in the second edition of Sustainable Safety (Wegman, Aarts and van der Knaap, 2022), namely:

- **Forgivingness:** This includes both physical (road environment) and social (road user) forgivingness. Physical forgivingness implies forgiving road designs, meaning they are built to reduce the severity of crashes when they occur. Social forgivingness implies that there is a mutual understanding between different types of road users, and these users are aware that mistakes can happen and therefore must be ready to accommodate accordingly.

- **State awareness:** Road users should be aware of their own physical and mental state and adjust their behaviour accordingly. This involves public education campaigns to raise awareness about the dangers of impaired driving, fatigue, and distraction, as well as encouraging self-regulation among drivers.

The most recent revision of the Sustainable Safety approach, outlined in the report "Sustainable Safety 3rd edition – The advanced vision for 2018-2030" published in 2018, marked the third and current phase of Sustainable Safety implementation. The third edition of Sustainable Safety aimed to revitalise the philosophy of Sustainable Safety by continuing to adapt and evolve previous and existing measures related to Sustainable Safety and to align it more with current societal trends, such as demographic changes, increasing urbanisation and technological developments (Wegman, Aarts and van der Knaap, 2022). This edition also pays more explicit attention towards mitigating and preventing bicycle crashes that do not involve motorised vehicles, emphasising the use of technological solutions as a way to complement infrastructural measures to achieve a desired result, allocating responsibility more effectively among road safety stakeholders in the event of a crash (including traffic professionals), and the use and development of risk factors or safety performance indicators (SPIs) as a basis for policy making (SWOV, 2018; Wegman, Aarts and van der Knaap, 2022).

In line with the updated focus on current road safety priorities and an expanded philosophy, the third edition of Sustainable Safety includes five key principles: Three "design" principles and two "organisation" principles (Wegman, Aarts and van der Knaap, 2022; SWOV, 2018; 2019). The three design principles correspond more or less with the principles that have been stipulated in previous editions, while the increased emphasis on the organisational aspects of road safety has led to the introduction of the two organisation principles. The three design principles are:

- **Functionality:** Remains the same as previous editions, as it provides a solid basis for the vision.

- **(Bio)mechanics:** Combines the old principles of homogeneity and forgivingness. This principle is about minimising the differences in speed, direction, mass and size of vehicles, while also affording maximum protection to road users.

- **Psychologics:** Combines the old principles of predictability and state awareness. This principle is about aligning the design of the road environment with the competencies and expectations of road users.

The two organisation principles are:

- **Responsibility:** Effectively allocated among stakeholders to guarantee maximum safety.

- **Learning and innovating:** Continuously improving the traffic system through innovation and adaptation.

Throughout its development, the Sustainable Safety vision has been characterized by its proactive and comprehensive nature, involving a wide range of stakeholders, including government agencies, municipalities, researchers, and the public. By adhering to its principles, the Sustainable Safety vision aims to create a road system that is inherently safer and more forgiving, reducing the likelihood and severity of accidents and promoting safer behaviour among all road users. This comprehensive and proactive strategy has contributed significantly to the improvement of road safety in the Netherlands, and has ultimately made Dutch roads among the safest in the world.

Table A.3. Evolution of Sustainable Safety principles (SWOV, 2019).

Towards a sustainably safe road traffic (1992-2010)	Advancing Sustainable Safety (2005-2020)	Sustainable Safety, third edition (2018-2030)
Functionality of roads	Functionality of roads	**Functionality** of roads
Homogeneity in mass, speed and direction	Homogeneity in mass, speed and direction	**(Bio)mechanics**: aligning speed, direction, mass, size and protection of road users
	Physical forgivingness Social forgivingness	
Predictability of traffic behaviour by recognizable road design	Recognizable road design, predictable road course and behaviour	**Psychologics**: aligning the traffic environment and competencies of road users
	Status awareness	
		Effectively allocating **responsibility**
		Learning and innovating in the traffic system

Appendix A.5: Road classification in the Netherlands

As outlined in the vision of Sustainable Safety, the principle of road functionality provides an important foundation for ensuring maximum road safety throughout the Dutch road network. In order to achieve this, the principle follows the concept of "mono-functionality", in which road sections and intersections have (ideally) only one function for all modes of transport (SWOV, 2018; 2019). Two types of functions are distinguished in this case: A traffic flow function and an exchange function. Traffic flow implies that traffic participation does not involve interaction with the surrounding environment, while exchange implies traffic participation involving interaction with the environment which may result in abrupt manoeuvres (SWOV, 2018; 2019). The main purpose of a traffic flow function is to move vehicles as quickly and as efficiently as possible from point A to point B, by minimising interactions and conflicts with other road users (particularly those who are vulnerable such as pedestrians and cyclists) and by limiting access points to certain properties (such as residential dwellings and businesses) that would result in abrupt manoeuvres. An exchange function on the other hand involves interactions and potential conflicts with other (vulnerable) road users, as well as allowing access to properties that serve as origin and destination points. The nature of an exchange function requires slower speeds to be driven, therefore a road section or an intersection with an exchange function cannot be combined safely with a traffic flow function which typically involves higher vehicle speeds, and as a result the two functions are kept separate in principle (SWOV, 2018; 2019).

To further illustrate how these two functions are applied to the road network, a distinction is made between dwelling areas and traffic areas. Dwelling areas consist of spaces where people live, work and recreate (i.e. residential and commercial zones), while traffic areas consist of road sections and intersections to which the principle of road functionality typically applies (SWOV, 2018; 2019). In principle, dwelling functions cannot be combined safely with traffic functions (due to high pedestrian volumes and/or children playing on the street, as well as nuisance-related issues), but in practice it is sometimes necessary to combine the two for accessibility reasons (e.g. access to homes and businesses). As a result, dwelling areas typically have an exchange function while traffic areas that purely serve transportation purposes have a traffic flow function. In some cases, areas that serve both a dwelling and a traffic purpose can result in a combination of exchange and flow functions (e.g. flow on road sections and exchange on intersections).

In order to establish a clear hierarchy of the road network based on the functions they serve, three road categories have been defined for Dutch roads (SWOV, 2018; 2019; 2023):

- **Through roads (*stroomwegen*):** These are roads with a purely traffic flow function (on road sections and intersections). They allow traffic to travel from origin to destination as quickly and as safely as possible. Motor traffic has the highest priority, and there are no conflicts or interactions with road users using slower modes of transport (such as mopeds, bicycles and pedestrians, as they are forbidden from using these roads). Examples of these types of roads include trunk roads and highways, and are only situated outside urban areas.

Figure A.6. Example of a through road.

- **Distributor roads (*gebiedsontsluitingswegen*, or GOW):** These are roads that have a traffic flow function on road sections and an exchange function at intersections. They connect through roads with access roads, and are found in both urban and rural areas. Traffic is typically separated on road sections (e.g. dedicated bike path for cyclists) while points of conflict may arise at intersections (e.g. pedestrians crossing the road).

Figure A.7. Example of a distributor road.

- **Access roads (*erftoegangswegen*, or ETW):** These are roads that purely have an exchange function (on road sections and intersections). They offer direct access to residential areas and locations of origin and destination. The residential function is prioritised which requires motor traffic to adapt by travelling at slower speeds. Traffic is usually mixed which results in potential conflict with other (vulnerable) road users. Just like distributor roads, access roads can also be found in both urban and rural areas.

Figure A.8. Example of an access road.

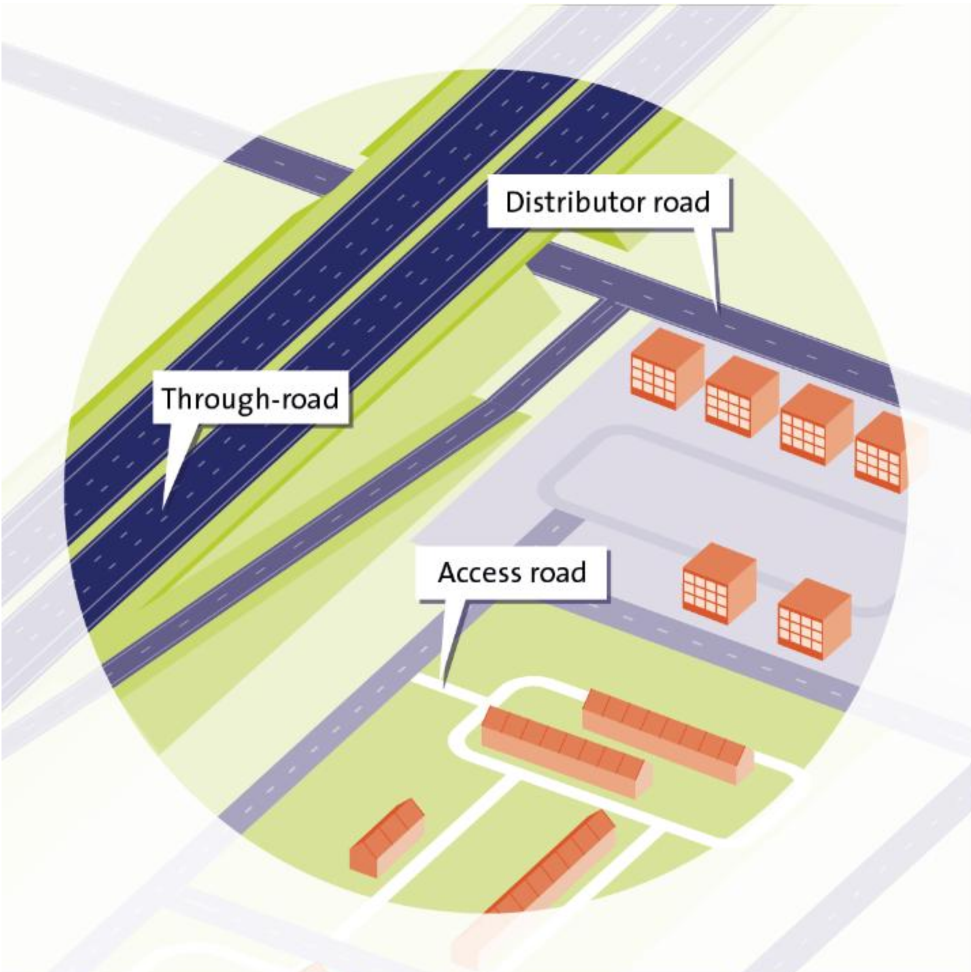


Figure A.9. Functional classification of the Dutch road network (SWOV, 2019).

Due to the functional nature of each road category, different speed limits are set based on what is considered safe and appropriate for that particular road category. These speed limits arise from the Sustainable Safety principle of (bio)mechanics, in which safe speeds are determined depending on the potential for conflict with other road users. Table A.4 shows what speeds are considered safe according to the potential and nature of conflicts with other (vulnerable) road users.

Table A.4. Safe speeds according to potential and types of conflicts (SWOV, 2019; 2021).

Potential conflicts and requirements associated with	**Safe speed (km/h)**
Possible conflicts with vulnerable road users in home zones (no foot paths and pedestrians using the carriageway)	**15**
Possible conflicts with vulnerable road users **on roads and at intersections, including situations with bike lanes or advisory bike lanes**	**30**
No conflicts with vulnerable road users, except with helmet-protected riders of motorised two-wheelers (mopeds on the carriageway). Possible right-angle conflicts between motorised vehicles, possible frontal conflicts between motorised vehicles. **Stopping sight distance ≥ 47 m**	**50**
No conflicts with vulnerable road users **No right-angle conflicts between motorised vehicles,** possible frontal conflicts between motorised vehicles **Obstacles shielded or obstacle-free zone ≥ 2.5 m, (semi)hard shoulder** **Stopping sight distance ≥ 64 m**	**60**
No conflicts with vulnerable road users No right-angle conflicts between motorised vehicles, possible frontal conflicts between motorised vehicles Obstacles shielded or **obstacle-free zone ≥ 4.5 m,** (semi)hard shoulder **Stopping sight distance ≥ 82 m**	**70**
No conflicts with vulnerable road users **No right-angle or frontal conflicts between motorised vehicles** Obstacles shielded or **obstacle-free zone ≥ 6 m,** (semi)hard shoulder **Stopping sight distance ≥ 105 m**	**80**
No conflicts with vulnerable road users No right-angle or frontal conflicts between motorised vehicles Obstacles shielded or **obstacle-free zone ≥ 10 m, hard shoulder** **Stopping sight distance ≥ 170 m**	**100**
No conflicts with vulnerable road users No right-angle or frontal conflicts between motorised vehicles Obstacles shielded or **obstacle-free zone ≥ 13 m**, hard shoulder **Stopping sight distance ≥ 260 m**	**120**
No conflicts with vulnerable road users No right-angle or frontal conflicts between motorised vehicles Obstacles shielded or **obstacle-free zone ≥ 14.5 m**, hard shoulder **Stopping sight distance ≥ 315 m**	**130**

For through roads, the maximum speed limit is set at 130 km/h for highways. However, as of March 2020, the standard daytime speed limit for highways (applied between 6 AM and 7 PM) is set at 100 km/h and, in some cases, a nighttime speed limit (between 7 PM and 6 AM the following day) of 120 km/h is applied (SWOV, 2021; 2023). This speed limit reduction is due to environmental reasons which will not be further elaborated upon. A (temporary) speed limit of 80 km/h may also be applied at some locations depending on road, traffic, weather and other environmental conditions. For rural trunk roads in particular, the speed limit is generally set at 100 km/h.

Higher speed limits can be set for through roads due to the fact that there is no potential for conflict with vulnerable road users, as these roads are exclusively reserved for high-speed traffic.

Additionally, there is no possibility for right-angle or frontal collisions as highway intersections are grade-separated and driving directions are physically separated by a median strip or a buffer zone with guardrails (SWOV, 2023). The presence of hard shoulders on these roads creates a forgiving road environment which allows fast-moving traffic to flow more safely and provides room for error so that the likelihood and severity of accidents can be minimised.

Figure A.10. Time-dependent speed limits for highways.

In direct contrast to through roads, access roads (ETW) have the lowest speed limits out of the three road categories. For urban areas, the speed limit for access roads is typically set at 30 km/h, while in rural areas the speed limit is 60 km/h. In special cases such as “home zones” (*woonerf* in Dutch), the speed limit can be as low as 15 km/h. This is due to the fact that home zones typically do not have separate infrastructural provisions for pedestrians and cyclists, and therefore pedestrians may use the whole width of the street for walking and/or playing (SWOV, 2023). These home zones are not only found in residential areas, but can also be applied to shopping streets and around train stations.

The lower speed limits set for access roads can be rationalised due to the high potential for conflict with vulnerable road users. Cyclists (as well as pedestrians in some cases) share the road with motor vehicles, so drivers need to adapt by driving at slower speeds. This is further encouraged through the use of physical speed-reducing measures such as speed humps and raised intersections, as a way to increase compliance with the speed limit and make the speed limit more credible. Access roads in urban areas are easily recognisable by its red brick surfaces and the “Zone 30” signs at entry/exit points of residential areas, further indicating to the driver that slow speeds are meant to be driven in these zones. In rural areas, “Zone 60” signs are used and roads are paved with asphalt, but are demarcated with edge strips that results in a visual narrowing of the road and therefore gives an indication to the driver that the speed limit is 60 km/h (SWOV, 2023).

Figure A.11. Zone 30 road sign.

Figure A.12. Zone 60 road sign.

Figure A.13. Rural access road.

The standard speed limit for urban distributor roads (GOW) is 50 km/h, sometimes referred to as GOW50. In some cases, a speed limit of 70 km/h can be applied, depending on the location and the design of the road. Distributor roads are either one or two lanes wide in each direction and are typically paved with asphalt, resulting in a clear distinction between GOW and ETW in urban areas. In rural areas, distributor roads have a speed limit of 80 km/h, and are recognisable by its characteristic double centre line markings which acts as a small buffer between the two driving directions, thereby reducing the potential for head-on conflicts (SWOV, 2023).

Figure A.14. Rural distributor road.

Because traffic flow is the primary function on GOW road sections, motor traffic and vulnerable road users are physically separated. This is preferably done by providing cyclists with a dedicated bicycle path, but in many cases a bicycle gutter (special lane for bicycles on the main carriageway), albeit less safe, is used instead (SWOV, 2023). Light moped users generally have to use the bicycle paths, while users of faster mopeds (with a top speed of 50 km/h) must use the carriageway, unless if the speed limit is 70 km/h. Principally speaking, physical speed-reducing measures are applied to road sections in a limited number of cases, but are more commonly applied to intersections where exchange occurs. Such measures may include roundabouts, speed humps and raised intersections, among others.

Figure A.15. Dedicated bike path along a distributor road.

Figure A.16. Bicycle gutter along a distributor road.

As mentioned previously, it is not always possible to separate residential and traffic functions on some road sections. As a result, some roads classified as GOW serve both functions, leading to the existence of so-called "grey roads" in which their primary function remains unclear (CROW, 2021; Goudappel, 2023). In addition, some of these roads lack proper infrastructural provisions for cyclists due to spatial limitations, therefore a 50 km/h speed limit would be considered unsafe and inappropriate. For these reasons, a new type of distributor road was recently introduced: A distributor road with a standard speed limit of 30 km/h (GOW30).

In late 2020, the Dutch parliament adopted GOW30 as a leading principle for setting safe speed limits within urban areas (Goudappel, 2023; SWOV, 2021). This means that a 50 km/h speed limit can only be applied if the design of the road (given the necessary provisions for vulnerable users) deems it safe to do so. This not only applies to roads that have a double function (traffic and residential), but also to roads that primarily have a traffic function. The main reason for the adoption of GOW30 is mostly due to safety, but other reasons such as improving liveability, reducing air and noise pollution, improving space-efficiency and improving social inclusivity are also major motivations for reducing the speed limit (Goudappel, 2023). In order to determine whether a road should have a 30 km/h or a 50 km/h speed limit, an assessment framework was developed by the independent knowledge platform CROW that provides guidance for road authorities and municipalities in determining appropriate road categories and speed limits based on a variety of considerations. This assessment framework is shown in Appendix A.6.

Appendix A.6: Assessment framework GOW30

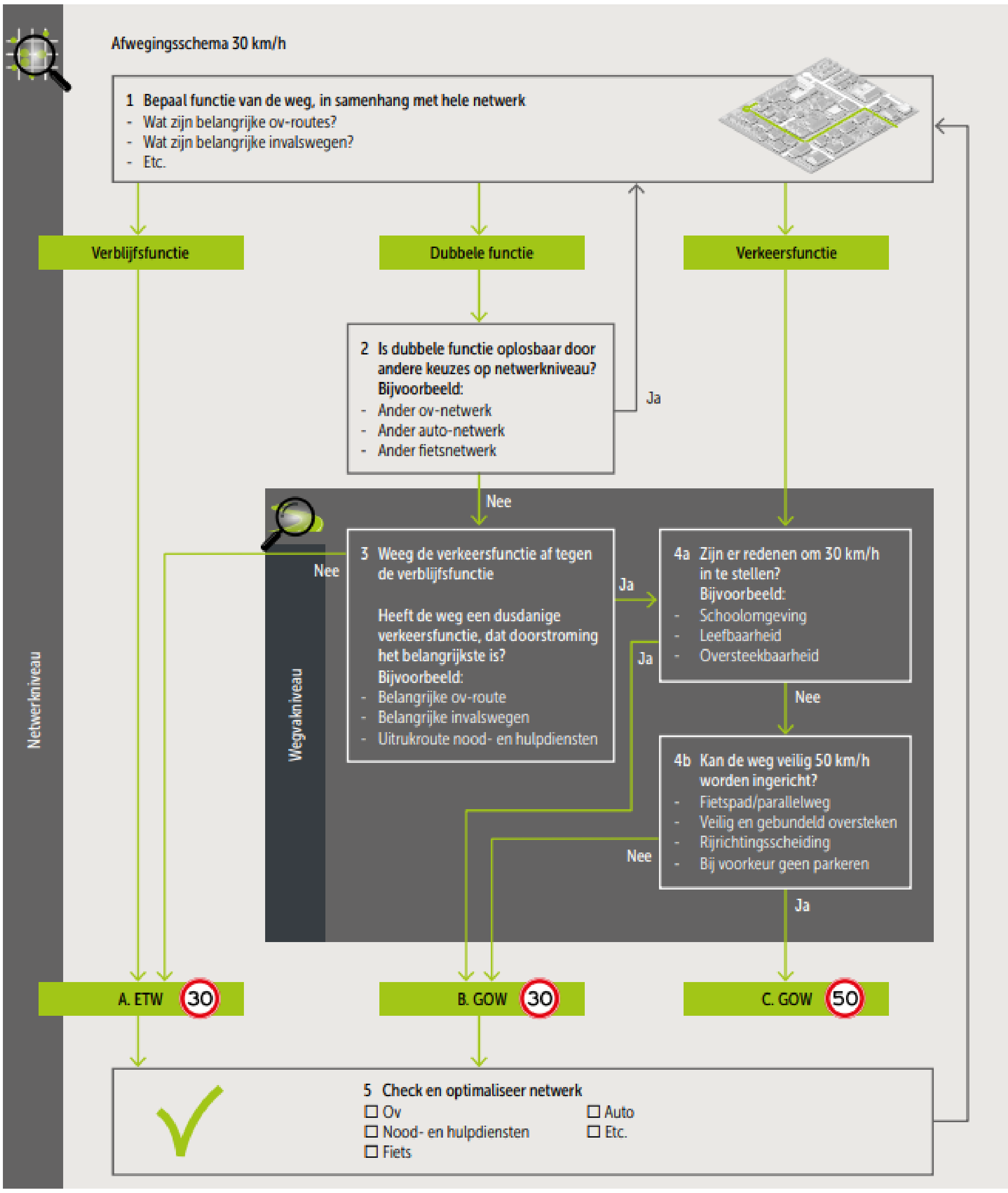


Figure A.17. Assessment framework for determining road classification and speed limit (CROW, 2021).

Appendix B: Case selection of road segments

Figure B.1. Westplantsoen, Delft.

Figure B.2. Proveniersplein, Rotterdam.

Figure B.3. Fluwelensingel, Gouda.

Figure B.4. Rijnstraat, Woerden.

Figure B.5. Albatrosstraat, Utrecht.

Figure B.6. Wittevrouwensingel, Utrecht.

Figure B.7. Weerdsingel Westzijde, Utrecht.

Figure B.8. Hopakker, Utrecht.

Figure B.9. Draaiweg, Utrecht.

Figure B.10. Nieuwendammerdijk, Amsterdam.

Figure B.11. Adriaan Loosjesstraat, Amsterdam.

Figure B.12. Beemsterstraat, Amsterdam.

Figure B.13. Meerpad, Amsterdam.

Figure B.14. Vogelenzangseweg, Vogelenzang.

Figure B.15. Utrechtseweg, Amersfoort.

Figure B.16. Vlasakkerweg, Amersfoort.

Figure B.17. Noordewierweg, Amersfoort.

Figure B.18. Bisschopsweg, Amersfoort.

Figure B.19. Eemnesserweg, Baarn.

Figure B.20. Drakenburgerweg, Baarn.

Figure B.21. Plataanlaan, Baarn.

Figure B.22. Zandstraat, Veenendaal.

Figure B.23. Kanaalweg, Veenendaal.

Figure B.24. Munnikenweg, Veenendaal.

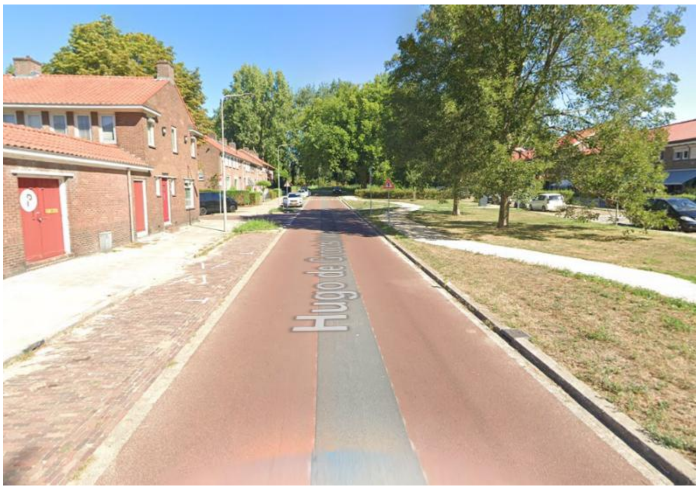


Figure B.25. Hugo de Grootstraat, Arnhem.

Figure B.26. Heijenoordseweg, Arnhem.

Figure B.27. Brouwerijweg, Arnhem.

Figure B.28. Spijkerstraat, Arnhem.

Figure B.29. Geestersingel, Alkmaar.

Figure B.30. Gabriël Metsulaan, Eindhoven.

Appendix C: Survey questionnaire

Questionnaire on the credibility of speed limits based on road design

This questionnaire is conducted as part of a Master's thesis project investigating drivers' perception of how the design of a road influences the credibility of its speed limit. A speed limit is considered credible when it matches the design or the layout of the road, as well as the surrounding context, so that drivers are more likely to comply with the limit (e.g. a 30 km/h speed limit is considered more credible for a narrow one-way street in a residential area than a 50 km/h speed limit). Many cities and towns in the Netherlands are planning to make a 30 km/h speed limit the norm for most of their urban distributor roads ("gebiedsontsluitingswegen" in Dutch) in an effort to improve road safety and liveability, as opposed to a 50 km/h speed limit that is currently applied. Some cities such as Amsterdam have already made this transition, but whether or not the new speed limit is deemed credible and if drivers actually comply with it remains to be seen.

To that end, the purpose of this questionnaire is to understand which road design elements contributes to how credible a speed limit is perceived. A series of questions will be asked regarding demographic characteristics (such as age and gender) as well as a set of 8 scenario-based questions, in which different road scenarios (images) are given and you are asked to give your perception of what the speed limit is, your perception of safety when driving or cycling at a given speed limit, and how credible you think a certain speed limit is based on the design of the road. The questionnaire should take approximately 10 minutes to complete and all responses are processed anonymously.

By continuing with the questionnaire, you agree to your responses being collected for analysis purposes. The questionnaire is completely voluntary and you may quit at any time without consequence.

Demographic information

1

Age *

- ◯ 18-24
- ◯ 25-34
- ◯ 35-44
- ◯ 45-54
- ◯ 55-64
- ◯ 65+

2

Gender *

- ◯ Male
- ◯ Female
- ◯ Other/prefer not to say

3

What mode of transport do you use most often? *

- ◯ Car
- ◯ Bike
- ◯ E-bike (up to 25 km/h)
- ◯ Speed pedelec (up to 45 km/h)
- ◯ Public transport
- ◯ Moped
- ◯ Walking
- ◯ Other

4

Do you have a driver's license? (Can be from any country) *

- ◯ Yes
- ◯ No

Driving information

5

Years of driving experience *

- ◯ Less than 2 years
- ◯ 2 to 4 years
- ◯ 4 to 6 years
- ◯ 6 to 8 years
- ◯ 8 to 10 years
- ◯ More than 10 years

6

How often do you drive? *

- ◯ Everyday
- ◯ A few times a week
- ◯ A few times a month
- ◯ A few times a year/rarely
- ◯ Never

7

Do you own a car? *

- ◯ Yes
- ◯ No

Scenario-based question 1

8

What do you think is the speed limit on this road? *

- ◯ 30 km/h
- ◯ 50 km/h
- ◯ Other

9

Answer this question from the perspective of a driver if the car is your most common mode of transportation. For all other modes of transport, answer this question from the perspective of a cyclist.

How safe would you feel travelling on this road at the given speed limit? *

	Very safe	Somewhat safe	Neither safe nor unsafe	Somewhat unsafe	Very unsafe
Less than 30 km/h	◯	◯	◯	◯	◯
30 km/h	◯	◯	◯	◯	◯
50 km/h	◯	◯	◯	◯	◯
More than 50 km/h	◯	◯	◯	◯	◯

10

How credible do you perceive the following speed limits to be for this road? *

	Very credible	Somewhat credible	Neutral	Somewhat not credible	Not credible at all
30 km/h	◯	◯	◯	◯	◯
50 km/h	◯	◯	◯	◯	◯

Scenario-based question 2

11

What do you think is the speed limit on this road? *

- 30 km/h
- 50 km/h
- Other

12

Answer this question from the perspective of a driver if the car is your most common mode of transportation. For all other modes of transport, answer this question from the perspective of a cyclist.

How safe would you feel travelling on this road at the given speed limit? *

	Very safe	Somewhat safe	Neither safe nor unsafe	Somewhat unsafe	Very unsafe
Less than 30 km/h	○	○	○	○	○
30 km/h	○	○	○	○	○
50 km/h	○	○	○	○	○
More than 50 km/h	○	○	○	○	○

13

How credible do you perceive the following speed limits to be for this road? *

	Very credible	Somewhat credible	Neutral	Somewhat not credible	Not credible at all
30 km/h	◯	◯	◯	◯	◯
50 km/h	◯	◯	◯	◯	◯

Scenario-based question 3

14

What do you think is the speed limit on this road? *

◯ 30 km/h

◯ 50 km/h

◯ Other

15

Answer this question from the perspective of a driver if the car is your most common mode of transportation. For all other modes of transport, answer this question from the perspective of a cyclist.

How safe would you feel travelling on this road at the given speed limit? *

	Very safe	Somewhat safe	Neither safe nor unsafe	Somewhat unsafe	Very unsafe
Less than 30 km/h	◯	◯	◯	◯	◯
30 km/h	◯	◯	◯	◯	◯
50 km/h	◯	◯	◯	◯	◯
More than 50 km/h	◯	◯	◯	◯	◯

16

How credible do you perceive the following speed limits to be for this road? *

	Very credible	Somewhat credible	Neutral	Somewhat not credible	Not credible at all
30 km/h	◯	◯	◯	◯	◯
50 km/h	◯	◯	◯	◯	◯

Scenario-based question 4

17

What do you think is the speed limit on this road? *

- 30 km/h
- 50 km/h
- Other

18

Answer this question from the perspective of a driver if the car is your most common mode of transportation. For all other modes of transport, answer this question from the perspective of a cyclist.

How safe would you feel travelling on this road at the given speed limit? *

	Very safe	Somewhat safe	Neither safe nor unsafe	Somewhat unsafe	Very unsafe
Less than 30 km/h	○	○	○	○	○
30 km/h	○	○	○	○	○
50 km/h	○	○	○	○	○
More than 50 km/h	○	○	○	○	○

19

How credible do you perceive the following speed limits to be for this road? *

	Very credible	Somewhat credible	Neutral	Somewhat not credible	Not credible at all
30 km/h	○	○	○	○	○
50 km/h	○	○	○	○	○

Scenario-based question 5

20

What do you think is the speed limit on this road? *

- 30 km/h
- 50 km/h
- Other

21

Answer this question from the perspective of a driver if the car is your most common mode of transportation. For all other modes of transport, answer this question from the perspective of a cyclist.

How safe would you feel travelling on this road at the given speed limit? *

	Very safe	Somewhat safe	Neither safe nor unsafe	Somewhat unsafe	Very unsafe
Less than 30 km/h	○	○	○	○	○
30 km/h	○	○	○	○	○
50 km/h	○	○	○	○	○
More than 50 km/h	○	○	○	○	○

22

How credible do you perceive the following speed limits to be for this road? *

	Very credible	Somewhat credible	Neutral	Somewhat not credible	Not credible at all
30 km/h	○	○	○	○	○
50 km/h	○	○	○	○	○

Scenario-based question 6

23

What do you think is the speed limit on this road? *

- 30 km/h
- 50 km/h
- Other

24

Answer this question from the perspective of a driver if the car is your most common mode of transportation. For all other modes of transport, answer this question from the perspective of a cyclist.

How safe would you feel travelling on this road at the given speed limit? *

	Very safe	Somewhat safe	Neither safe nor unsafe	Somewhat unsafe	Very unsafe
Less than 30 km/h	○	○	○	○	○
30 km/h	○	○	○	○	○
50 km/h	○	○	○	○	○
More than 50 km/h	○	○	○	○	○

25

How credible do you perceive the following speed limits to be for this road? *

	Very credible	Somewhat credible	Neutral	Somewhat not credible	Not credible at all
30 km/h	○	○	○	○	○
50 km/h	○	○	○	○	○

Scenario-based question 7

26

What do you think is the speed limit on this road? *

- 30 km/h
- 50 km/h
- Other

27

Answer this question from the perspective of a driver if the car is your most common mode of transportation. For all other modes of transport, answer this question from the perspective of a cyclist.

How safe would you feel travelling on this road at the given speed limit? *

	Very safe	Somewhat safe	Neither safe nor unsafe	Somewhat unsafe	Very unsafe
Less than 30 km/h	◯	◯	◯	◯	◯
30 km/h	◯	◯	◯	◯	◯
50 km/h	◯	◯	◯	◯	◯
More than 50 km/h	◯	◯	◯	◯	◯

28

How credible do you perceive the following speed limits to be for this road? *

	Very credible	Somewhat credible	Neutral	Somewhat not credible	Not credible at all
30 km/h	◯	◯	◯	◯	◯
50 km/h	◯	◯	◯	◯	◯

Scenario-based question 8

29

What do you think is the speed limit on this road? *

◯ 30 km/h

◯ 50 km/h

◯ Other

30

Answer this question from the perspective of a driver if the car is your most common mode of transportation. For all other modes of transport, answer this question from the perspective of a cyclist.

How safe would you feel travelling on this road at the given speed limit? *

	Very safe	Somewhat safe	Neither safe nor unsafe	Somewhat unsafe	Very unsafe
Less than 30 km/h	○	○	○	○	○
30 km/h	○	○	○	○	○
50 km/h	○	○	○	○	○
More than 50 km/h	○	○	○	○	○

31

How credible do you perceive the following speed limits to be for this road? *

	Very credible	Somewhat credible	Neutral	Somewhat not credible	Not credible at all
30 km/h	○	○	○	○	○
50 km/h	○	○	○	○	○

Concluding questions

32

Which road characteristic(s) do you think affects the credibility of a speed limit the most? (Multiple answers possible) *

- [ ] Road/lane width
- [ ] Presence of road/lane markings
- [ ] Presence of bike lanes
- [ ] Type of road surface (e.g. asphalt or brick)
- [ ] Presence of tree linings
- [ ] Presence of parked cars
- [ ] Other

33

Any final remarks/comments?

Appendix D: Descriptive tables and graphs of road segment characteristics

Speed limit

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	30 km/h	420	70.0	70.0	70.0
	50 km/h	180	30.0	30.0	100.0
	Total	600	100.0	100.0	

Table D.1. Observation frequency per speed limit category.

Number of lanes

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	1 lane	580	96.7	96.7	96.7
	2 lanes	20	3.3	3.3	100.0
	Total	600	100.0	100.0	

Table D.2. Observation frequency per lane category.

One-way street

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	No	380	63.3	63.3	63.3
	Yes	220	36.7	36.7	100.0
	Total	600	100.0	100.0	

Table D.3. Observation frequency per street classification (one-way or bi-directional).

Lane markings

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	No	480	80.0	80.0	80.0
	Yes	120	20.0	20.0	100.0
	Total	600	100.0	100.0	

Table D.4. Observation frequency of lane marking characteristics.

Road surface

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Brick	280	46.7	46.7	46.7
	Dyed asphalt	40	6.7	6.7	53.3
	Grey asphalt	280	46.7	46.7	100.0
	Total	600	100.0	100.0	

Table D.5. Observation frequency of road surface characteristics.

Bike lanes

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	None	200	33.3	33.3	33.3
	Mix gutter/none	20	3.3	3.3	36.7
	Gutter	300	50.0	50.0	86.7
	Mix gutter/separated	40	6.7	6.7	93.3
	Separated	40	6.7	6.7	100.0
	Total	600	100.0	100.0	

Table D.6. Observation frequency of bike lane characteristics.

On-street parking

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	No	120	20.0	20.0	20.0
	Yes	480	80.0	80.0	100.0
	Total	600	100.0	100.0	

Table D.7. Observation frequency of on-street parking characteristics.

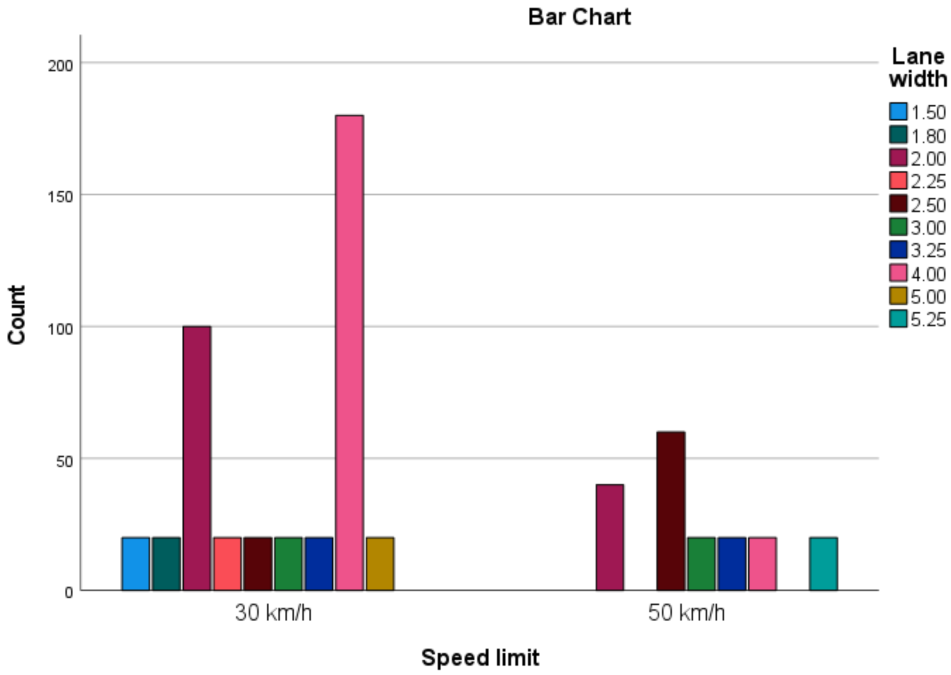


Figure D.1. Frequency distribution of observed lane widths categorised by speed limit.

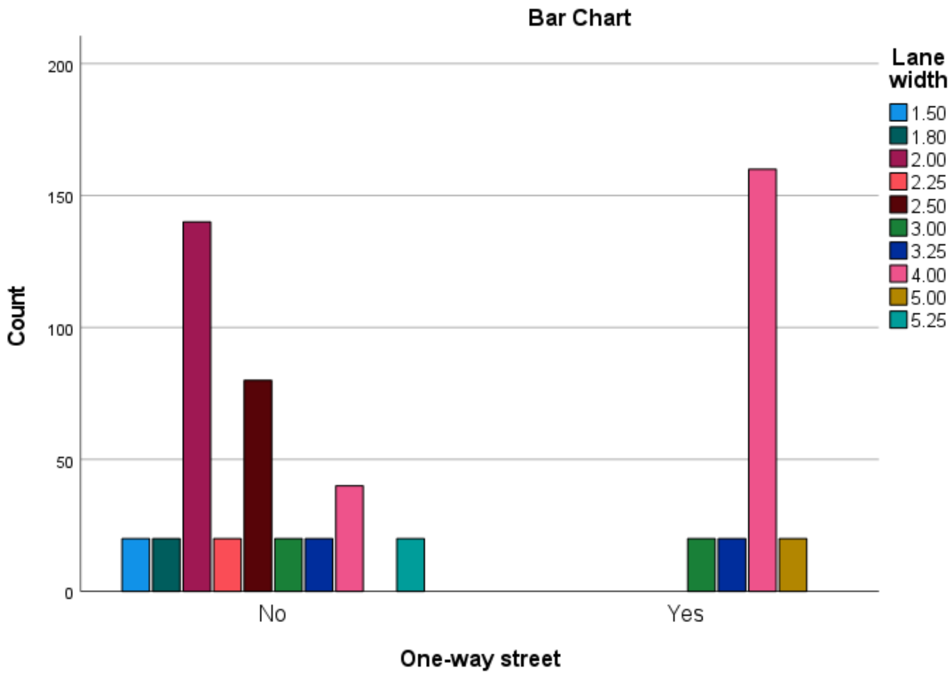


Figure D.2. Frequency distribution of observed lane widths categorised by street classification (one-way or bi-directional).

Appendix E: Statistical results of individual road characteristic effects on vehicle speed

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
V85 speed	412	36.999	11.0859	.5462
Speed limit	420	30.00	.000[a]	.000

a. t cannot be computed because the standard deviation is 0.

Table E.1. Mean V85 speed on 30 km/h roads.

One-Sample Test

	Test Value = 30						
			Significance			95% Confidence Interval of the Difference	
	t	df	One-Sided p	Two-Sided p	Mean Difference	Lower	Upper
V85 speed	12.814	411	<.001	<.001	6.9988	5.925	8.072

Table E.2. One-sample t-test result for mean V85 speed on 30 km/h roads.

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
V85 speed	180	45.706	9.0379	.6736
Speed limit	180	50.00	.000[a]	.000

a. t cannot be computed because the standard deviation is 0.

Table E.3. Mean V85 speed on 50 km/h roads.

One-Sample Test

	Test Value = 50						
			Significance			95% Confidence Interval of the Difference	
	t	df	One-Sided p	Two-Sided p	Mean Difference	Lower	Upper
V85 speed	-6.375	179	<.001	<.001	-4.2944	-5.624	-2.965

Table E.4. One-sample t-test result for mean V85 speed on 50 km/h roads.

Group Statistics

	One-way street	N	Mean	Std. Deviation	Std. Error Mean
V85 speed	No	235	35.106	11.7909	.7692
	Yes	177	39.511	9.5406	.7171

Table E.5. Mean V85 speeds driven on one-way streets and bi-directional roads with a 30 km/h speed limit.

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means							
						Significance				95% Confidence Interval of the Difference	
		F	Sig.	t	df	One-Sided p	Two-Sided p	Mean Difference	Std. Error Difference	Lower	Upper
V85 speed	Equal variances assumed	2.849	.092	-4.067	410	<.001	<.001	-4.4049	1.0830	-6.5339	-2.2759
	Equal variances not assumed			-4.189	407.871	<.001	<.001	-4.4049	1.0516	-6.4721	-2.3377

Table E.6. Two-sample t-test result for mean V85 speeds driven on one-way streets and bi-directional roads with a 30 km/h speed limit.

Group Statistics

	One-way street	N	Mean	Std. Deviation	Std. Error Mean
V85 speed	No	140	47.011	9.4659	.8000
	Yes	40	41.138	5.2951	.8372

Table E.7. Mean V85 speeds driven on one-way streets and bi-directional roads with a 50 km/h speed limit.

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means							
						Significance				95% Confidence Interval of the Difference	
		F	Sig.	t	df	One-Sided p	Two-Sided p	Mean Difference	Std. Error Difference	Lower	Upper
V85 speed	Equal variances assumed	3.623	.059	3.755	178	<.001	<.001	5.8732	1.5641	2.7866	8.9598
	Equal variances not assumed			5.072	115.675	<.001	<.001	5.8732	1.1580	3.5796	8.1669

Table E.8. Two-sample t-test result for mean V85 speeds driven on one-way streets and bi-directional roads with a 50 km/h speed limit.

Correlations[a]

		V85 speed	Lane width
Pearson Correlation	V85 speed	1.000	-.099
	Lane width	-.099	1.000
Sig. (1-tailed)	V85 speed	.	.022
	Lane width	.022	.
N	V85 speed	412	412
	Lane width	412	412

a. Selecting only cases for which Speed limit = 30 km/h

Table E.9. Correlations between lane width and V85 speed on 30 km/h roads.

Model Summary[b,c]

	R					Change Statistics					Durbin-Watson Statistic	
Model	Speed limit = 30 km/h (Selected)	Speed limit ~= 30 km/h (Unselected)	R Square	Adjusted R Square	Std. Error of the Estimate	R Square Change	F Change	df1	df2	Sig. F Change	Speed limit = 30 km/h (Selected)	Speed limit ~= 30 km/h (Unselected)
1	.099[a]	.	.010	.007	11.0446	.010	4.082	1	410	.044	.543	.127

a. Predictors: (Constant), Lane width

b. Unless noted otherwise, statistics are based only on cases for which Speed limit = 30 km/h.

c. Dependent Variable: V85 speed

Table E.10. R-squared values of the linear regression model between lane width and V85 speed on 30 km/h roads.

Coefficients[a,b]

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.	95.0% Confidence Interval for B Lower Bound	95.0% Confidence Interval for B Upper Bound	Correlations Zero-order	Correlations Partial	Correlations Part	Collinearity Statistics Tolerance	Collinearity Statistics VIF
1	(Constant)	40.286	1.716		23.482	<.001	36.913	43.658					
	Lane width	-1.061	.525	-.099	-2.020	.044	-2.094	-.029	-.099	-.099	-.099	1.000	1.000

a. Dependent Variable: V85 speed

b. Selecting only cases for which Speed limit = 30 km/h

Table E.11. Regression coefficients of lane width on 30 km/h roads.

Correlations[a]

		V85 speed	Lane width
Pearson Correlation	V85 speed	1.000	.618
	Lane width	.618	1.000
Sig. (1-tailed)	V85 speed	.	<.001
	Lane width	.000	.
N	V85 speed	180	180
	Lane width	180	180

a. Selecting only cases for which Speed limit = 50 km/h

Table E.12. Correlations between lane width and V85 speed on 50 km/h roads.

Model Summary[b,c]

Model	R Speed limit = 50 km/h (Selected)	R Speed limit ~= 50 km/h (Unselected)	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics R Square Change	Change Statistics F Change	Change Statistics df1	Change Statistics df2	Change Statistics Sig. F Change	Durbin-Watson Statistic Speed limit = 50 km/h (Selected)	Durbin-Watson Statistic Speed limit ~= 50 km/h (Unselected)
1	.618[a]	.	.382	.378	7.1257	.382	109.957	1	178	<.001	.376	.278

a. Predictors: (Constant), Lane width

b. Unless noted otherwise, statistics are based only on cases for which Speed limit = 50 km/h.

c. Dependent Variable: V85 speed

Table E.13. R-squared values of the linear regression model between lane width and V85 speed on 50 km/h roads.

Coefficients[a,b]

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.	95.0% Confidence Interval for B Lower Bound	95.0% Confidence Interval for B Upper Bound	Correlations Zero-order	Correlations Partial	Correlations Part	Collinearity Statistics Tolerance	Collinearity Statistics VIF
1	(Constant)	28.880	1.690		17.087	<.001	25.545	32.216					
	Lane width	5.608	.535	.618	10.486	<.001	4.553	6.664	.618	.618	.618	1.000	1.000

a. Dependent Variable: V85 speed

b. Selecting only cases for which Speed limit = 50 km/h

Table E.14. Regression coefficients of lane width on 50 km/h roads.

Group Statistics

	Lane markings	N	Mean	Std. Deviation	Std. Error Mean
V85 speed	No	392	37.528	11.1027	.5608
	Yes	20	26.625	1.6212	.3625

Table E.15. Mean V85 speeds on roads with and without lane markings present (30 km/h speed limit).

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means							
						Significance				95% Confidence Interval of the Difference	
		F	Sig.	t	df	One-Sided p	Two-Sided p	Mean Difference	Std. Error Difference	Lower	Upper
V85 speed	Equal variances assumed	18.133	<.001	4.384	410	<.001	<.001	10.9031	2.4868	6.0146	15.7915
	Equal variances not assumed			16.328	171.114	<.001	<.001	10.9031	.6677	9.5850	12.2211

Table E.16. Two-sample t-test result for mean V85 speeds on roads with and without lane markings present (30 km/h speed limit).

Group Statistics

	Lane markings	N	Mean	Std. Deviation	Std. Error Mean
V85 speed	No	80	45.919	4.0678	.4548
	Yes	100	45.535	11.5940	1.1594

Table E.17. Mean V85 speeds on roads with and without lane markings present (50 km/h speed limit).

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means							
						Significance				95% Confidence Interval of the Difference	
		F	Sig.	t	df	One-Sided p	Two-Sided p	Mean Difference	Std. Error Difference	Lower	Upper
V85 speed	Equal variances assumed	58.857	<.001	.282	178	.389	.778	.3838	1.3592	-2.2984	3.0659
	Equal variances not assumed			.308	128.013	.379	.758	.3838	1.2454	-2.0805	2.8480

Table E.18. Two-sample t-test result for mean V85 speeds on roads with and without lane markings present (50 km/h speed limit).

Descriptives

V85 speed

		N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean: Lower Bound	95% Confidence Interval for Mean: Upper Bound	Minimum	Maximum	Between-Component Variance
Brick		232	35.438	12.9511	.8503	33.762	37.113	11.0	71.5	
Dyed asphalt		40	35.313	5.3249	.8419	33.610	37.015	27.0	53.5	
Grey asphalt		140	40.068	7.8937	.6671	38.749	41.387	26.5	70.0	
Total		412	36.999	11.0859	.5462	35.925	38.072	11.0	71.5	
Model	Fixed Effects			10.8910	.5366	35.944	38.054			
	Random Effects				1.9165	28.753	45.245			7.6586

Table E.19. Mean V85 speeds on various road surfaces with a 30 km/h speed limit.

ANOVA

V85 speed

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1997.957	2	998.978	8.422	<.001
Within Groups	48512.793	409	118.613		
Total	50510.749	411			

Table E.20. ANOVA result for mean V85 speeds on various road surfaces with a 30 km/h speed limit.

Group Statistics

	Road surface	N	Mean	Std. Deviation	Std. Error Mean
V85 speed	Brick	40	46.263	1.9381	.3064
	Grey asphalt	140	45.546	10.1991	.8620

Table E.21. Mean V85 speeds on brick and asphalt surfaces with a 50 km/h speed limit.

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means							
						Significance		Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
		F	Sig.	t	df	One-Sided p	Two-Sided p			Lower	Upper
V85 speed	Equal variances assumed	37.822	<.001	.441	178	.330	.660	.7161	1.6240	-2.4887	3.9209
	Equal variances not assumed			.783	166.856	.217	.435	.7161	.9148	-1.0901	2.5222

Table E.22. Two-sample t-test result for mean V85 speeds on brick and asphalt surfaces with a 50 km/h speed limit.

Descriptives

V85 speed

		N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum	Between-Component Variance
						Lower Bound	Upper Bound			
None		192	35.060	9.5756	.6911	33.697	36.423	11.0	65.5	
Mix gutter/none		20	33.375	6.6330	1.4832	30.271	36.479	24.0	48.0	
Gutter		160	39.247	13.7039	1.0834	37.107	41.387	11.0	71.5	
Mix gutter/separated		40	39.125	2.9017	.4588	38.197	40.053	34.0	49.5	
Total		412	36.999	11.0859	.5462	35.925	38.072	11.0	71.5	
Model	Fixed Effects			10.9070	.5373	35.942	38.055			
	Random Effects				1.6407	31.777	42.220			6.3279

Table E.23. Mean V85 speeds on roads with various bike lane characteristics (30 km/h speed limit).

ANOVA

V85 speed

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1973.877	3	657.959	5.531	<.001
Within Groups	48536.872	408	118.963		
Total	50510.749	411			

Table E.24. ANOVA result for mean V85 speeds on roads with various bike lane characteristics (30 km/h speed limit).

Group Statistics

	Bike lanes	N	Mean	Std. Deviation	Std. Error Mean
V85 speed	Gutter	140	46.950	9.4785	.8011
	Separated	40	41.350	5.4481	.8614

Table E.25. Mean V85 speeds on roads with gutter and separated bike lanes (50 km/h speed limit).

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						95% Confidence Interval of the Difference	
						Significance					
		F	Sig.	t	df	One-Sided p	Two-Sided p	Mean Difference	Std. Error Difference	Lower	Upper
V85 speed	Equal variances assumed	3.204	.075	3.567	178	<.001	<.001	5.6000	1.5698	2.5023	8.6977
	Equal variances not assumed			4.761	112.100	<.001	<.001	5.6000	1.1763	3.2692	7.9308

Table E.26. Two-sample t-test result for mean V85 speeds on roads with gutter and separated bike lanes (50 km/h speed limit).

Group Statistics

	On-street parking	N	Mean	Std. Deviation	Std. Error Mean
V85 speed	No	40	35.088	5.0254	.7946
	Yes	372	37.204	11.5350	.5981

Table E.27. Mean V85 speeds on roads with and without on-street parking present (30 km/h speed limit).

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						95% Confidence Interval of the Difference	
						Significance					
		F	Sig.	t	df	One-Sided p	Two-Sided p	Mean Difference	Std. Error Difference	Lower	Upper
V85 speed	Equal variances assumed	17.922	<.001	-1.148	410	.126	.252	-2.1168	1.8440	-5.7416	1.5080
	Equal variances not assumed			-2.128	92.581	.018	.036	-2.1168	.9945	-4.0918	-.1418

Table E.28. Two-sample t-test result for mean V85 speeds on roads with and without on-street parking present (30 km/h speed limit).

Group Statistics

	On-street parking	N	Mean	Std. Deviation	Std. Error Mean
V85 speed	No	80	41.919	4.8714	.5446
	Yes	100	48.735	10.3873	1.0387

Table E.29. Mean V85 speeds on roads with and without on-street parking present (50 km/h speed limit).

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						95% Confidence Interval of the Difference	
						Significance					
		F	Sig.	t	df	One-Sided p	Two-Sided p	Mean Difference	Std. Error Difference	Lower	Upper
V85 speed	Equal variances assumed	23.192	<.001	-5.410	178	<.001	<.001	-6.8162	1.2598	-9.3024	-4.3301
	Equal variances not assumed			-5.812	146.995	<.001	<.001	-6.8162	1.1729	-9.1341	-4.4984

Table E.30. Two-sample t-test result for mean V85 speeds on roads with and without on-street parking present (50 km/h speed limit).

Appendix F: Statistical results of combined road characteristic effects on vehicle speed (GLM)

Tests of Between-Subjects Effects

Dependent Variable: V85 speed

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	15824.203[a]	11	1438.564	14.189	<.001	.212
Intercept	13784.260	1	13784.260	135.957	<.001	.190
speed_limit	2525.723	1	2525.723	24.912	<.001	.041
one_way	29.683	1	29.683	.293	.589	.001
lane_markings	730.672	1	730.672	7.207	.007	.012
road_surface	507.818	2	253.909	2.504	.083	.009
bike_lanes	2437.768	4	609.442	6.011	<.001	.040
on_street_parking	55.041	1	55.041	.543	.462	.001
lane_width	556.785	1	556.785	5.492	.019	.009
Error	58804.408	580	101.387			
Total	1005142.750	592				
Corrected Total	74628.611	591				

a. R Squared = .212 (Adjusted R Squared = .197)

Table F.1. Tests of between-subjects effects of road characteristics on V85 speed.

Parameter Estimates

Dependent Variable: V85 speed

Parameter	B	Std. Error	t	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound	Partial Eta Squared
Intercept	39.419	3.836	10.275	<.001	31.885	46.954	.154
[speed_limit=30]	-7.595	1.522	-4.991	<.001	-10.584	-4.606	.041
[speed_limit=50]	0[a]	.	.	.	.	.	.
[one_way=0]	-.854	1.579	-.541	.589	-3.956	2.247	.001
[one_way=1]	0[a]	.	.	.	.	.	.
[lane_markings=0]	5.028	1.873	2.685	.007	1.350	8.707	.012
[lane_markings=1]	0[a]	.	.	.	.	.	.
[road_surface=0]	-2.470	1.127	-2.191	.029	-4.684	-.256	.008
[road_surface=1]	-.516	1.975	-.261	.794	-4.395	3.363	.000
[road_surface=2]	0[a]	.	.	.	.	.	.
[bike_lanes=0]	-5.919	3.071	-1.927	.054	-11.951	.114	.006
[bike_lanes=1]	-7.124	3.748	-1.901	.058	-14.485	.237	.006
[bike_lanes=2]	.390	2.570	.152	.879	-4.657	5.437	.000
[bike_lanes=3]	-3.035	3.421	-.887	.375	-9.754	3.683	.001
[bike_lanes=4]	0[a]	.	.	.	.	.	.
[on_street_parking=0]	-1.225	1.662	-.737	.462	-4.489	2.040	.001
[on_street_parking=1]	0[a]	.	.	.	.	.	.
lane_width	1.835	.783	2.343	.019	.297	3.373	.009

a. This parameter is set to zero because it is redundant.

Table F.2. GLM parameter estimates of road characteristic effects on V85 speed.

Appendix G: Graphical and chi-square results of associations between road characteristics and speed limit perception

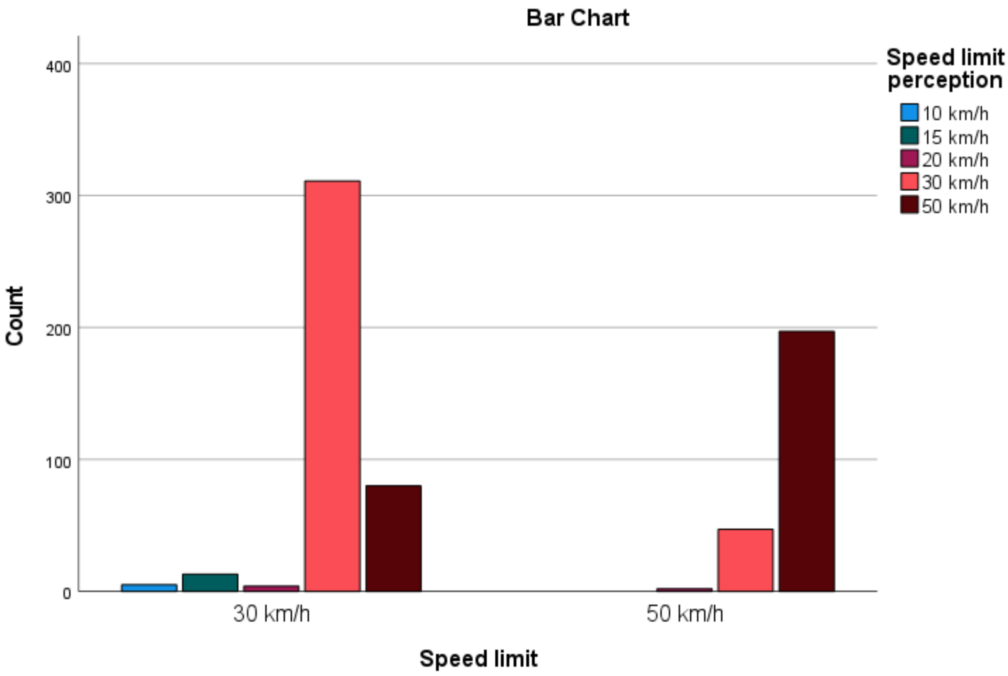


Figure G.1. Association between actual speed limits and speed limit perception.

Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	235.575[a]	4	<.001
Likelihood Ratio	251.749	4	<.001
Linear-by-Linear Association	222.537	1	<.001
N of Valid Cases	659		

a. 5 cells (50.0%) have expected count less than 5. The minimum expected count is 1.87.

Table G.1. Chi-square test result of the association between actual speed limits and speed limit perception.

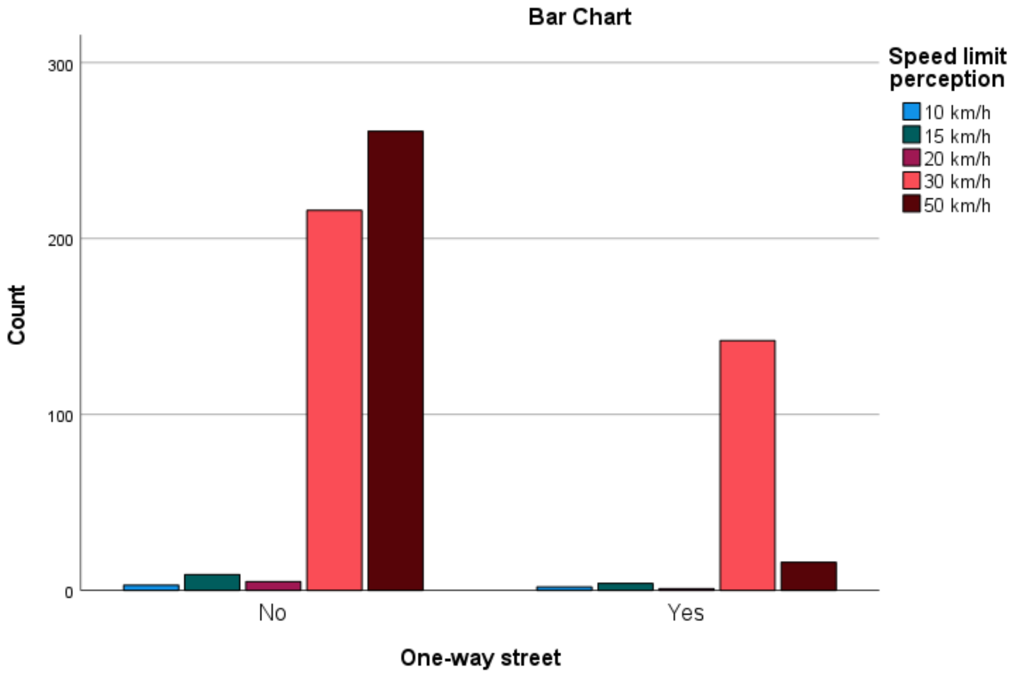


Figure G.2. Association between one-way streets and speed limit perception.

Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	96.612[a]	4	<.001
Likelihood Ratio	110.332	4	<.001
Linear-by-Linear Association	83.409	1	<.001
N of Valid Cases	659		

a. 5 cells (50.0%) have expected count less than 5. The minimum expected count is 1.25.

Table G.2. Chi-square test result of the association between one-way streets and speed limit perception.

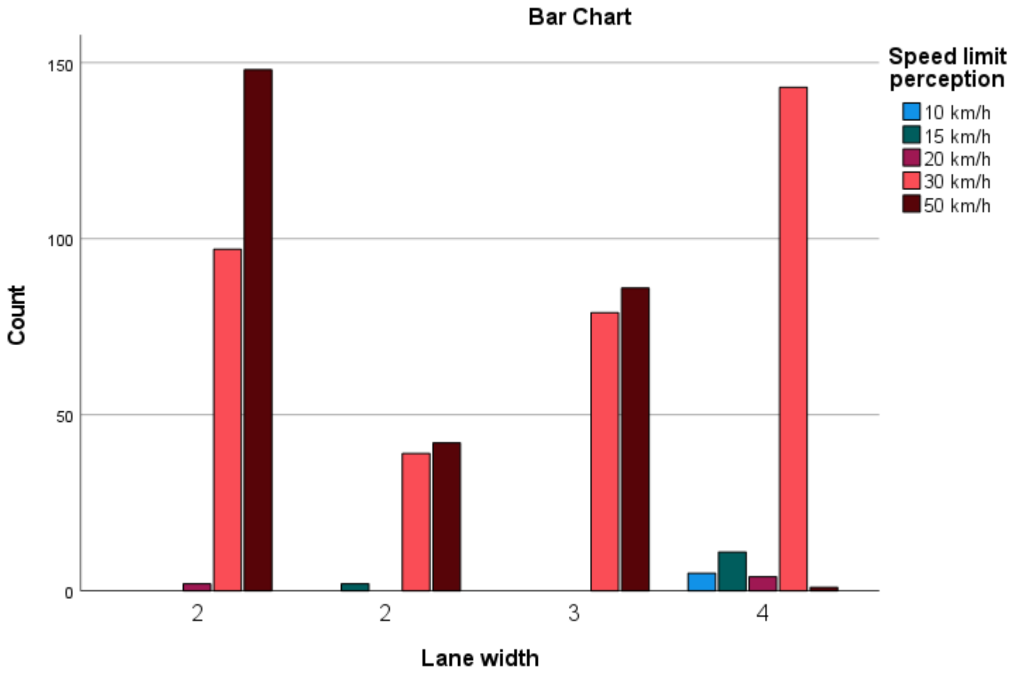


Figure G.3. Association between lane width and speed limit perception.

Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	184.627[a]	12	<.001
Likelihood Ratio	239.207	12	<.001
Linear-by-Linear Association	148.058	1	<.001
N of Valid Cases	659		

a. 12 cells (60.0%) have expected count less than 5. The minimum expected count is .63.

Table G.3. Chi-square test result of the association between lane width and speed limit perception.

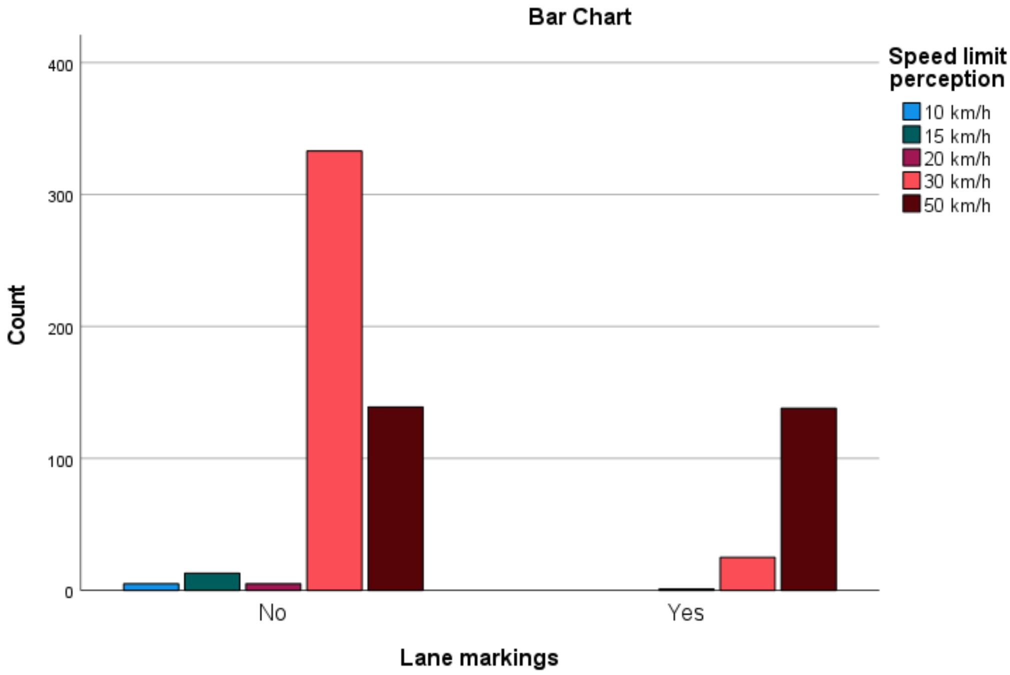


Figure G.4. Association between presence of lane markings and speed limit perception.

Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	159.686[a]	4	<.001
Likelihood Ratio	168.804	4	<.001
Linear-by-Linear Association	150.676	1	<.001
N of Valid Cases	659		

a. 5 cells (50.0%) have expected count less than 5. The minimum expected count is 1.24.

Table G.4. Chi-square test result of the association between lane marking presence and speed limit perception.

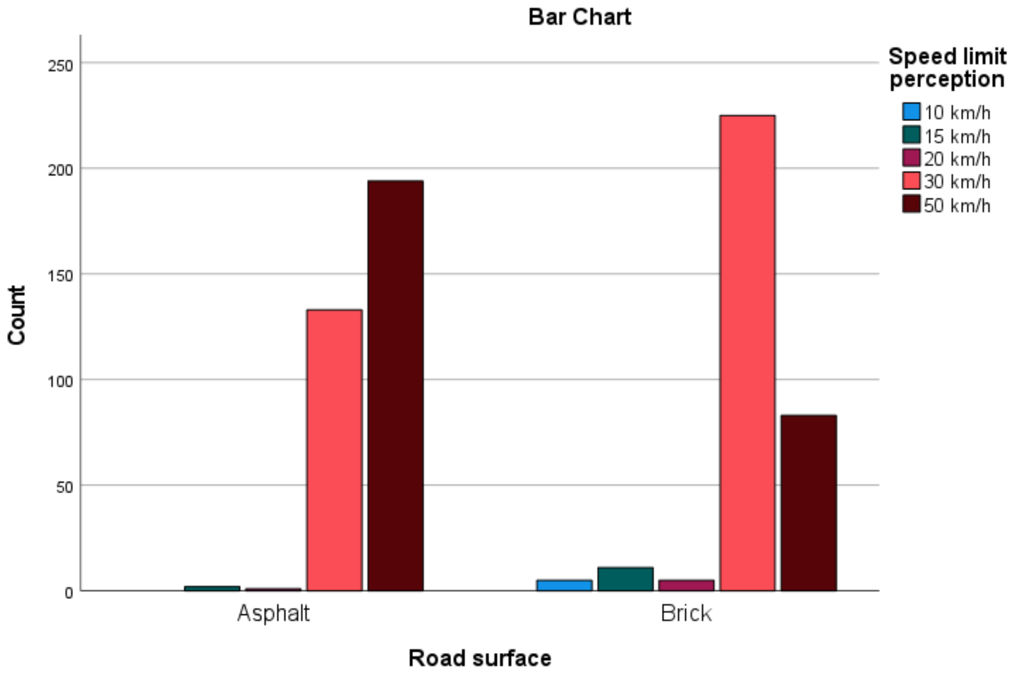


Figure G.5. Association between road surface type and speed limit perception.

Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	82.019[a]	4	<.001
Likelihood Ratio	86.365	4	<.001
Linear-by-Linear Association	81.775	1	<.001
N of Valid Cases	659		

a. 4 cells (40.0%) have expected count less than 5. The minimum expected count is 2.50.

Table G.5. Chi-square test result of the association between road surface type and speed limit perception.

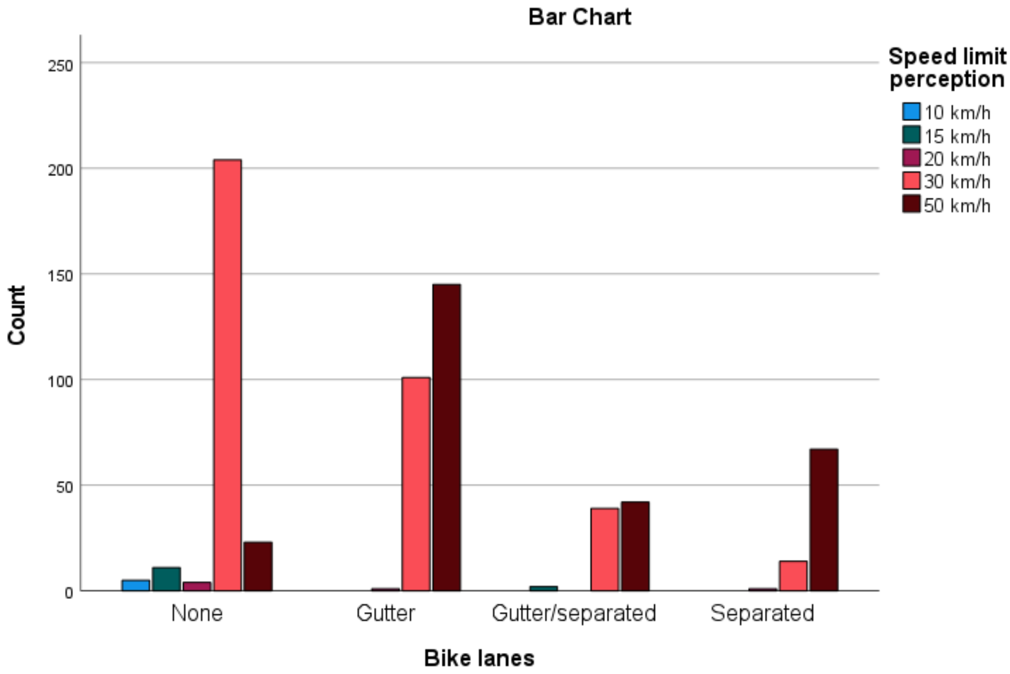


Figure G.6. Association between bike lanes and speed limit perception.

Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	203.223[a]	12	<.001
Likelihood Ratio	234.105	12	<.001
Linear-by-Linear Association	145.496	1	<.001
N of Valid Cases	659		

a. 12 cells (60.0%) have expected count less than 5. The minimum expected count is .62.

Table G.6. Chi-square test result of the association between bike lanes and speed limit perception.

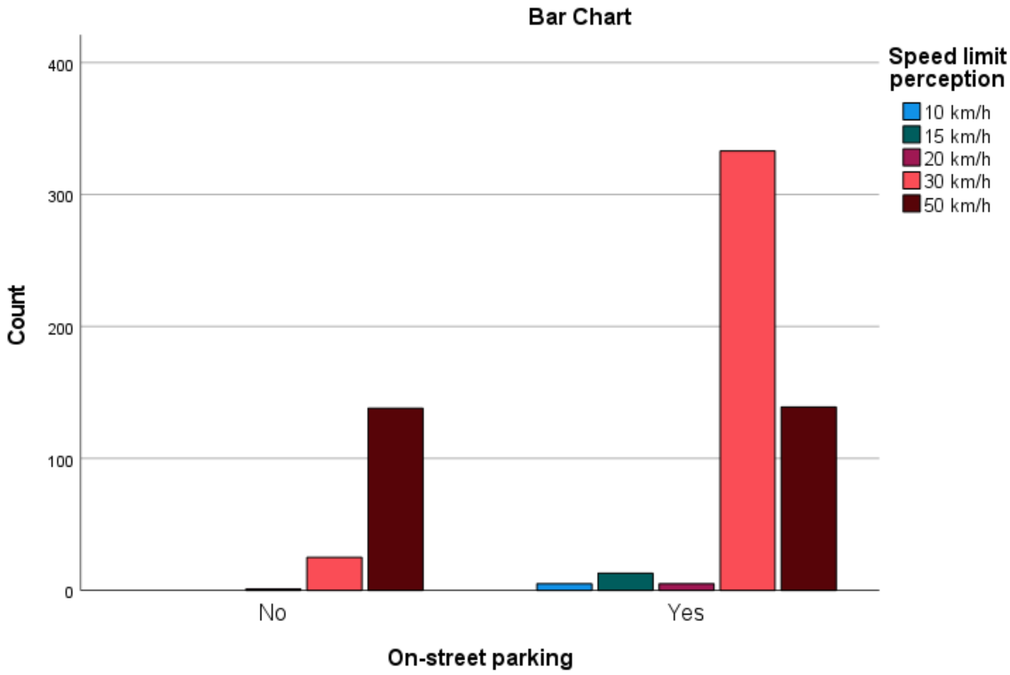


Figure G.7. Association between on-street parking presence and speed limit perception.

Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	159.686[a]	4	<.001
Likelihood Ratio	168.804	4	<.001
Linear-by-Linear Association	150.676	1	<.001
N of Valid Cases	659		

a. 5 cells (50.0%) have expected count less than 5. The minimum expected count is 1.24.

Table G.7. Chi-square test result of the association between on-street parking presence and speed limit perception.

Appendix H: Ordinal logistic regression results of associations between road characteristics and speed limit perception, safety perception and speed limit credibility perception

Parameter Estimates

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Threshold	[slpcat = .00]	-8.711	1.596	29.789	1	<.001	-11.839	-5.583
	[slpcat = 1.00]	-2.779	1.270	4.790	1	.029	-5.267	-.290
Location	lanewidth	-.325	.653	.248	1	.619	-1.605	.955
	[oneway=0]	-.646	.447	2.088	1	.148	-1.523	.230
	[oneway=1]	0[a]	.	.	0	.	.	.
	[lanemarkings=0]	-1.264	.844	2.245	1	.134	-2.917	.389
	[lanemarkings=1]	0[a]	.	.	0	.	.	.
	[roadsurface=0]	2.698	1.097	6.049	1	.014	.548	4.849
	[roadsurface=1]	0[a]	.	.	0	.	.	.
	[bikelanes=0]	-3.910	1.953	4.009	1	.045	-7.737	-.083
	[bikelanes=1]	-1.990	1.763	1.275	1	.259	-5.445	1.465
	[bikelanes=2]	-2.855	2.041	1.956	1	.162	-6.855	1.145
	[bikelanes=3]	0[a]	.	.	0	.	.	.
	[onstreetpark=0]	0[a]	.	.	0	.	.	.
	[onstreetpark=1]	0[a]	.	.	0	.	.	.

Link function: Logit.

a. This parameter is set to zero because it is redundant.

Table H.1. OLR parameter estimates of road characteristic effects on speed limit perception.

Parameter Estimates

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Threshold	[SRlessthan30 = 1]	-6.879	1.139	36.465	1	<.001	-9.112	-4.647
	[SRlessthan30 = 2]	-5.469	1.071	26.072	1	<.001	-7.568	-3.369
	[SRlessthan30 = 3]	-4.284	1.054	16.513	1	<.001	-6.350	-2.218
	[SRlessthan30 = 4]	-3.191	1.047	9.281	1	.002	-5.243	-1.138
Location	lanewidth	-1.062	.539	3.884	1	.049	-2.118	-.006
	[oneway=0]	.049	.363	.019	1	.892	-.661	.760
	[oneway=1]	0[a]	.	.	0	.	.	.
	[lanemarkings=0]	-1.448	.729	3.938	1	.047	-2.877	-.018
	[lanemarkings=1]	0[a]	.	.	0	.	.	.
	[roadsurface=0]	-1.518	.967	2.463	1	.117	-3.413	.378
	[roadsurface=1]	0[a]	.	.	0	.	.	.
	[bikelanes=0]	3.634	1.793	4.109	1	.043	.120	7.148
	[bikelanes=1]	2.740	1.525	3.230	1	.072	-.248	5.729
	[bikelanes=2]	3.141	1.795	3.063	1	.080	-.377	6.659
	[bikelanes=3]	0[a]	.	.	0	.	.	.
	[onstreetpark=0]	0[a]	.	.	0	.	.	.
	[onstreetpark=1]	0[a]	.	.	0	.	.	.

Link function: Logit.

a. This parameter is set to zero because it is redundant.

Table H.2. OLR parameter estimates of road characteristic effects on safety perception for speeds below 30 km/h.

Parameter Estimates

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Threshold	[SR30 = 1]	-5.924	1.085	29.810	1	<.001	-8.050	-3.797
	[SR30 = 2]	-4.222	.952	19.669	1	<.001	-6.087	-2.356
	[SR30 = 3]	-2.798	.927	9.120	1	.003	-4.614	-.982
	[SR30 = 4]	-1.161	.918	1.600	1	.206	-2.960	.638
Location	lanewidth	.271	.470	.333	1	.564	-.650	1.192
	[oneway=0]	-.619	.303	4.163	1	.041	-1.213	-.024
	[oneway=1]	0[a]	.	.	0	.	.	.
	[lanemarkings=0]	.476	.692	.474	1	.491	-.880	1.832
	[lanemarkings=1]	0[a]	.	.	0	.	.	.
	[roadsurface=0]	1.604	.869	3.408	1	.065	-.099	3.306
	[roadsurface=1]	0[a]	.	.	0	.	.	.
	[bikelanes=0]	-2.263	1.618	1.957	1	.162	-5.434	.907
	[bikelanes=1]	-2.001	1.366	2.147	1	.143	-4.679	.676
	[bikelanes=2]	-2.334	1.654	1.990	1	.158	-5.576	.909
	[bikelanes=3]	0[a]	.	.	0	.	.	.
	[onstreetpark=0]	0[a]	.	.	0	.	.	.
	[onstreetpark=1]	0[a]	.	.	0	.	.	.

Link function: Logit.

a. This parameter is set to zero because it is redundant.

Table H.3. OLR parameter estimates of road characteristic effects on safety perception for speeds at 30 km/h.

Parameter Estimates

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
Threshold	[SR50 = 1]	-3.219	.788	16.692	1	<.001	-4.763	-1.675
	[SR50 = 2]	-1.296	.773	2.809	1	.094	-2.811	.220
	[SR50 = 3]	-.586	.774	.573	1	.449	-2.102	.931
	[SR50 = 4]	.775	.778	.991	1	.319	-.750	2.300
Location	lanewidth	.359	.400	.805	1	.370	-.425	1.142
	[oneway=0]	-.563	.291	3.732	1	.053	-1.134	.008
	[oneway=1]	0[a]	.	.	0	.	.	.
	[lanemarkings=0]	-.124	.561	.049	1	.825	-1.225	.976
	[lanemarkings=1]	0[a]	.	.	0	.	.	.
	[roadsurface=0]	2.012	.752	7.154	1	.007	.538	3.486
	[roadsurface=1]	0[a]	.	.	0	.	.	.
	[bikelanes=0]	-3.670	1.358	7.303	1	.007	-6.331	-1.008
	[bikelanes=1]	-2.501	1.168	4.581	1	.032	-4.791	-.211
	[bikelanes=2]	-3.251	1.389	5.475	1	.019	-5.974	-.528
	[bikelanes=3]	0[a]	.	.	0	.	.	.
	[onstreetpark=0]	0[a]	.	.	0	.	.	.
	[onstreetpark=1]	0[a]	.	.	0	.	.	.

Link function: Logit.

a. This parameter is set to zero because it is redundant.

Table H.4. OLR parameter estimates of road characteristic effects on safety perception for speeds at 50 km/h.

Parameter Estimates

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
Threshold	[SRmorethan50 = 1]	-.288	.895	.104	1	.748	-2.042	1.466
	[SRmorethan50 = 2]	.727	.896	.658	1	.417	-1.030	2.483
	[SRmorethan50 = 3]	1.545	.900	2.949	1	.086	-.218	3.309
	[SRmorethan50 = 4]	2.356	.909	6.715	1	.010	.574	4.137
Location	lanewidth	.164	.470	.121	1	.728	-.758	1.086
	[oneway=0]	-.248	.384	.415	1	.519	-1.001	.506
	[oneway=1]	0[a]	.	.	0	.	.	.
	[lanemarkings=0]	-.282	.629	.201	1	.654	-1.514	.950
	[lanemarkings=1]	0[a]	.	.	0	.	.	.
	[roadsurface=0]	1.102	.900	1.500	1	.221	-.661	2.865
	[roadsurface=1]	0[a]	.	.	0	.	.	.
	[bikelanes=0]	-1.885	1.570	1.441	1	.230	-4.962	1.192
	[bikelanes=1]	-1.387	1.376	1.017	1	.313	-4.083	1.309
	[bikelanes=2]	-1.670	1.611	1.075	1	.300	-4.827	1.486
	[bikelanes=3]	0[a]	.	.	0	.	.	.
	[onstreetpark=0]	0[a]	.	.	0	.	.	.
	[onstreetpark=1]	0[a]	.	.	0	.	.	.

Link function: Logit.

a. This parameter is set to zero because it is redundant.

Table H.5. OLR parameter estimates of road characteristic effects on safety perception for speeds above 50 km/h.

Parameter Estimates

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Threshold	[CR30 = 1]	-4.615	.904	26.036	1	<.001	-6.388	-2.842
	[CR30 = 2]	-2.873	.882	10.612	1	.001	-4.602	-1.144
	[CR30 = 3]	-2.054	.878	5.469	1	.019	-3.776	-.333
	[CR30 = 4]	-.998	.875	1.300	1	.254	-2.713	.717
Location	lanewidth	-.812	.466	3.039	1	.081	-1.725	.101
	[oneway=0]	-.207	.354	.341	1	.559	-.901	.487
	[oneway=1]	0[a]	.	.	0	.	.	.
	[lanemarkings=0]	.046	.613	.006	1	.941	-1.156	1.247
	[lanemarkings=1]	0[a]	.	.	0	.	.	.
	[roadsurface=0]	-1.935	.880	4.831	1	.028	-3.660	-.210
	[roadsurface=1]	0[a]	.	.	0	.	.	.
	[bikelanes=0]	3.371	1.541	4.787	1	.029	.351	6.391
	[bikelanes=1]	2.371	1.354	3.067	1	.080	-.283	5.024
	[bikelanes=2]	3.062	1.579	3.759	1	.053	-.033	6.158
	[bikelanes=3]	0[a]	.	.	0	.	.	.
	[onstreetpark=0]	0[a]	.	.	0	.	.	.
	[onstreetpark=1]	0[a]	.	.	0	.	.	.

Link function: Logit.

a. This parameter is set to zero because it is redundant.

Table H.6. OLR parameter estimates of road characteristic effects on 30 km/h speed limit credibility perception.

Parameter Estimates

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Threshold	[CR50 = 1]	-2.847	.779	13.356	1	<.001	-4.374	-1.320
	[CR50 = 2]	-1.820	.771	5.579	1	.018	-3.330	-.310
	[CR50 = 3]	-1.138	.769	2.188	1	.139	-2.646	.370
	[CR50 = 4]	.120	.774	.024	1	.877	-1.397	1.636
Location	lanewidth	.107	.397	.073	1	.787	-.672	.886
	[oneway=0]	-.435	.298	2.140	1	.143	-1.019	.148
	[oneway=1]	0[a]	.	.	0	.	.	.
	[lanemarkings=0]	-.443	.564	.616	1	.432	-1.549	.663
	[lanemarkings=1]	0[a]	.	.	0	.	.	.
	[roadsurface=0]	1.795	.753	5.689	1	.017	.320	3.271
	[roadsurface=1]	0[a]	.	.	0	.	.	.
	[bikelanes=0]	-2.753	1.355	4.130	1	.042	-5.408	-.098
	[bikelanes=1]	-1.621	1.167	1.931	1	.165	-3.908	.666
	[bikelanes=2]	-2.354	1.389	2.871	1	.090	-5.076	.369
	[bikelanes=3]	0[a]	.	.	0	.	.	.
	[onstreetpark=0]	0[a]	.	.	0	.	.	.
	[onstreetpark=1]	0[a]	.	.	0	.	.	.

Link function: Logit.

a. This parameter is set to zero because it is redundant.

Table H.7. OLR parameter estimates of road characteristic effects on 50 km/h speed limit credibility perception.

Appendix I: Scientific article

Enhancing the Credibility of a 30 km/h Urban Speed Limit Through Road Design

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Highlights

- Drivers' 85th-percentile speeds (V85) exceed 30 km/h limits by ~7 km/h on average, indicating widespread non-compliance on 30 km/h roads and lack of credible design.
- Road design elements strongly shape both actual speeds and perceived credibility: Brick surfaces, minimal bicycle infrastructure, and narrower lanes support a 30 km/h speed limit; grey asphalt, bicycle separation, and wider lanes undermine it.
- Credibility is context-dependent: Asphalt surfaces decrease credibility at 30 km/h but increase credibility at 50 km/h; the presence/absence of bike lanes flips in the same way.
- A mixed-methods design (objective V85 from Telraam; n = 600 observations; and perceptions from an online survey; n = 83) triangulates design–risk–credibility relationships.

Abstract

Dutch municipalities are increasingly reclassifying urban distributor roads from 50 km/h (GOW50) to 30 km/h (GOW30). For this policy to succeed, speed limits must be credible (i.e., aligned with drivers' expectations formed by the visual and physical cues of the road). This study examines how road design features shape (i) actual vehicle speeds and (ii) drivers' perceptions of speed limit credibility and safety. A mixed-methods design combined objective speed measurements from 30 urban road segments in the Netherlands (600 observations; 70% at 30 km/h) with a perception survey (n=83). For speeds, descriptive analysis, t-tests/ANOVA, and a General Linear Model (GLM) were used; perceptions were analyzed using chi-square tests and Ordinal Logistic Regression (OLR). Key results: (1) Narrower lanes, brick surfaces, and the absence of bike lanes are associated with lower speeds; (2) in multivariate GLM, road surface, lane markings, bike lane configuration, and lane width are significant predictors; (3) credibility perceptions differ by context: Features that bolster a 30 km/h limit include brick surfaces, absent markings, and minimal/no bike separation, while a 50 km/h limit is seen as more credible when presented with asphalt surfaces and clearer separation. The findings provide empirical support for self-explaining road design and argue for design-led speed management to reinforce low-speed policy goals.

Keywords: Speed limit credibility; GOW30; self-explaining roads; risk perception; road safety; General Linear Model; Ordinal Logistic Regression; urban road design.

1. Introduction

Urban speed management is a central policy challenge for cities seeking to reduce fatalities, improve livability, and prioritize sustainable modes. In the Netherlands, the introduction of GOW30 aims to transition urban distributor roads from the standard 50 km/h to 30 km/h speed limits, in order to protect vulnerable road users and improve road safety overall (CROW, 2021; Röth, Koljensic and Kuipers, 2022), but success depends on whether drivers perceive the lower limit as credible. Credible limits are those "that meet expectations raised by the road and road environment" (SWOV, 2021), fostering compliance through visual design cues rather than enforcement alone. Research on self-explaining roads suggests that when the road environment aligns with the posted speed limit, drivers are more likely to comply (Ambros et al., 2021; Charlton and Starkey, 2017; Yao et al., 2019a; 2019b; 2020a; 2020b). However, the literature reveals several gaps: Most studies focus on high-speed or rural roads, rely on single-variable analyses, or lack robust empirical testing of credibility perceptions. This study addresses these gaps by analyzing the combined and individual effects of road design elements on both actual speeds and perceived credibility in low-speed urban contexts.

This study pursues the following main research question: *What road design characteristics are the most effective at enhancing the credibility of GOW30?* Three sub-questions are also addressed: (1) *Based on literature, what factors influence the credibility of a speed limit?* (2) *What are the effects of various road design characteristics on actual speeds being driven on urban roads?* And (3) *What are the effects of various road design characteristics on drivers' perceptions towards speed limit credibility and risk?*

2. Methodology

2.1 Study design

A mixed-methods design integrated:

1. **Objective speeds:** 85th percentile (V85) speeds collected from 30 urban road segments across Dutch cities via Telraam, a citizen-sensor network, yielding 600 hourly observations (measured on July 1–5, 2024; 07:00–11:00). Predictor (independent) variables included: Posted speed limit (30/50 km/h), one-way vs bi-directional street, lane width (in meters), presence of longitudinal markings (yes/no), road surface (brick, dyed-asphalt "bicycle street", grey asphalt), bike lane provision (none/gutter/separated/mixed), and presence of on-street parking (yes/no). All predictors are categorical with the exception of lane width (continuous). Outcome (dependent) variable: Hourly average V85 speed (continuous, in km/h).
2. **Subjective perceptions:** An online survey among Dutch residents (n = 83; conducted August 2024) presented eight road scenarios and elicited (i) perceived speed limit, (ii) perceived safety at four speed categories (<30 km/h, 30 km/h, 50 km/h, and >50 km/h), and (iii) perceived credibility of 30 km/h and 50 km/h speed limits. Perceived safety and credibility were assessed on a Likert scale (1: Not safe/credible at all, to 5: Very safe/credible). Responses were anonymous and ethical approval was secured from TU Delft HREC.

2.2 Data cleaning and analysis

Outlier V85 readings likely due to adverse weather were removed (n = 7), resulting in final hourly observations counts of 412 for 30 km/h road segments and 180 for 50 km/h road segments. Distinct high-speed clusters on two segments (Wittevrouwensingel, 30 km/h; and Geestersingel, 50 km/h) were retained as plausible design-driven phenomena. Statistical methods used to analyse predictor effects on V85 speeds include: Descriptive statistics regarding average speeds on 30 km/h and 50 km/h segments, one-sample and independent-samples t-tests for binary predictors (speed limit, one-way, lane markings, and on-street parking), one-way ANOVA for multi-level predictors (road surface and bike lane configuration), linear regression for continuous predictors (i.e., lane width, stratified by speed limit), and GLM including all design covariates (to measure combined effects). For the analysis of predictor effects on perceptions, chi-square tests were used to measure associations between predictors and perceived speed limits, and OLR was use to estimate direction/magnitude of effects for safety and credibility perceptions (30 km/h and 50 km/h models). Table 1 shows the data collection and analysis methods in an overview, arranged accordingly by sub-question.

Table 1. Overview of methods.

Sub-question	Data collection method	Data analysis method
4. *Based on literature, what factors influence the credibility of a speed limit?*	Literature review	Development of a conceptual model
5. *What are the effects of various road design characteristics on actual speeds being driven on urban roads?*	Speed and traffic data extracted from Telraam (open-source traffic database)	Analysis of descriptive statistics regarding road characteristics and average V85 speeds on selected road segments; utilisation of t-tests, linear regression and ANOVA to determine statistical differences in mean speeds between different road types
6. *What are the effects of various road design characteristics on drivers' perceptions towards speed limit credibility and risk?*	Online survey regarding speed limit perception, perceived safety and speed limit credibility perception	Analysis of descriptive statistics regarding perceived safety and speed limit credibility perception of certain road types; utilisation of chi-square tests and ordinal logistic regression to determine statistical significance of the credibility of different road types

3. Literature review

The literature conceptualizes speed limit credibility as the extent to which a posted speed limit matches with expectations set by the road environment (SWOV, 2021). When this match holds, compliance would likely improve. In experimental and field work, design features such as lane width, road geometry, and the surrounding environment shape drivers' risk perception, which then governs both perceived appropriate speed and chosen speed. This results in a relationship between three primary factors: Road environment, risk perception, and credibility/compliance, supported by various mixed-methods studies that explicitly model risk (Yao et al., 2019a; 2019b; 2020a; 2020b) and by studies linking perceived/posted/chosen speeds and road design elements (Ambros et al., 2021; Charlton & Starkey, 2017). This integrative view is adapted even further by situating road design alongside behavioural traits and contextual influences as co-determinants of credibility, creating an overarching conceptual framework that includes various external and internal influences (as seen in Figure 1).

Evidence on speed limit reductions generally indicates safety gains (Lu, Qurashi and Antoniou, 2023; Schaefer, Figliozzi and Unnikrishnan, 2022; Son et al., 2022; Zhai et al., 2022), with modest efficiency trade-offs that depend on network context (Cohen, Christoforou and Seidowsky, 2014; Gressai et al., 2021). Crucially, signage alone rarely sustains behavioural change. Credible speed limits require congruent self-explaining design (Mackie et al., 2013). Multi-city/segment analyses associate geometric narrowing, surface/marking treatments, pedestrian crossing density, sidewalks, road curvature, and land-use context with speed distributions, though effect sizes vary by setting (e.g., lane-width effects differ between Italy and the Czech Republic), underscoring the need for local calibration (Martinelli et al., 2022; Schano, Novy and Smisek, 2023).

A third strand examines public attitudes towards lower speed limits and perceived appropriate speeds. Survey-based studies links acceptance of lower limits to street design and certain demographic characteristics (including age and gender) and shows that perceived appropriate speed align with noticeable design elements (e.g., visual narrowing) and intended street function (e.g., high pedestrian activity) (Dinh and Kubota, 2013; Lahausse et al., 2010). Studies combining survey perception data with field observations corroborate that credibility is co-determined by design and subjective user interpretation (Gitelman, Pesahov and Carmel, 2020). It should be noted, however, multivariate evidence for urban 30 km/h contexts remains comparatively lacking, motivating the present study.

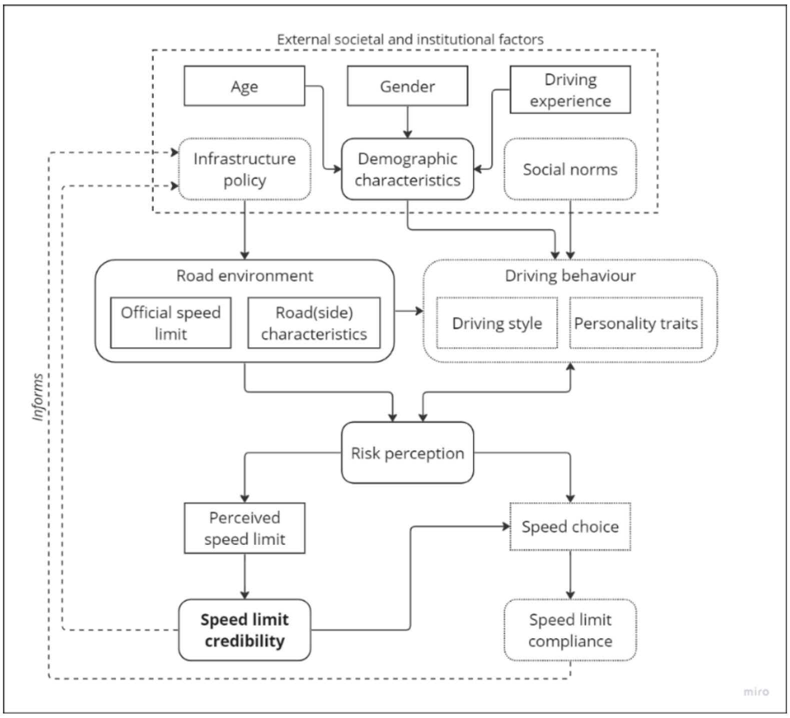

Figure 1. Conceptual model showing factors influencing speed limit credibility.

4. Results

4.1 Descriptive speeds

After outlier removal, mean V85 on 30 km/h segments was found to be ~37 km/h (SD ≈ 11.1), indicating a general attitude of non-compliance towards a 30 km/h speed limit (and less credibility therefore). On 50 km/h streets, mean V85 was found to be ~46 km/h (SD ≈ 9.0), indicating higher rates of compliance and higher credibility. One-sample t-tests showed that V85 on 30 km/h segments > 30 km/h ($p < 0.001$, mean difference ≈ +7 km/h), and V85 on 50 km/h segments < 50 km/h ($p < 0.001$, mean difference ≈ -4 km/h).

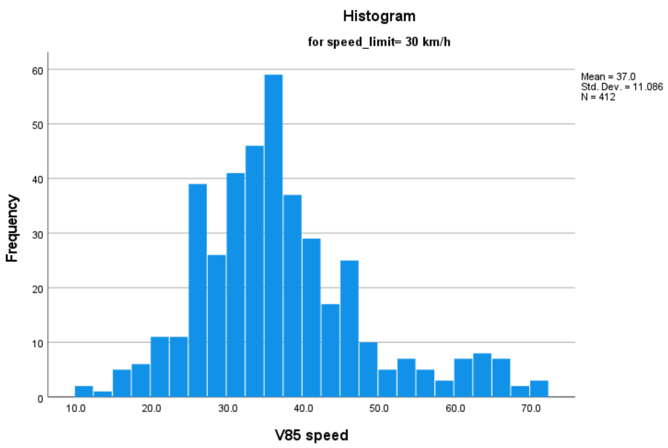

Figure 2. V85 speed distribution for 30 km/h roads.

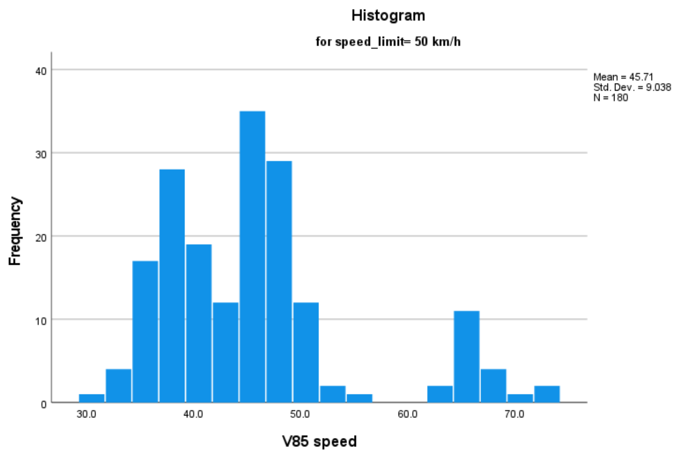

Figure 3. V85 speed distribution for 50 km/h roads.

4.2 Individual design effects on speed

Table 2 displays the main individual effects of each road design predictor on V85 speed for each speed limit category.

Table 2. Individual road characteristic effects on vehicle speed.

Road characteristic	Test method(s)	30 km/h speed limit	50 km/h speed limit
Speed limit	*One-sample t-test*	*Significant difference; mean speed higher than speed limit*	*Significant difference; mean speed lower than speed limit*
One-way street	*Two-sample t-test*	*Significant effect; mean speed higher on one-way streets*	*Significant effect; mean speed lower on one-way streets*
Lane width	*Linear regression*	*Weak negative relationship between speed and lane width; low R squared*	*Moderate positive relationship between speed and lane width; low R squared but higher than for 30 km/h roads*
Lane markings	*Two-sample t-test*	*Significant effect; mean speed lower on roads with lane markings (possible Type I error due to low sample size)*	*No significant effect on vehicle speed*
Road surface	*One-way ANOVA (30 km/h roads); two-sample t-test (50 km/h roads)*	*Significant effects; mean speed higher on grey asphalt roads than on brick and dyed asphalt roads. No significant difference*	*No significant effect on vehicle speed*

		between brick and dyed asphalt	
Bike lanes	*One-way ANOVA (30 km/h roads); two-sample t-test (50 km/h roads)*	*Significant effects; mean speed higher on roads with bicycle gutters than on roads with no bike lanes. Effects of mixed bike lane characteristics not significant*	*Significant effect; mean speed higher on roads with bicycle gutters than on roads with separated bike paths*
On-street parking	*Two-sample t-test*	*Significant effect; mean speed higher on roads with on-street parking (possible Type I error due to high sample imbalance)*	*Significant effect; mean speed higher on roads with on-street parking (effect more profound than on 30 km/h roads)*

4.3 Combined design effects on speed

When considering all road design predictors together and their combined effects on vehicle speed, the multivariate GLM indicates the following main effects of each predictor (full results shown in Tables 3 and 4):

- **Speed limit:** Strong main effect (30 vs. 50 km/h; $F=24.192$, $p<0.001$; B coefficient ≈ −7.6 km/h for 30 km/h).
- **Lane markings:** Significant effect ($F=7.207$, $p=0.007$); roads without markings exhibit higher speeds relative to marked roads (B ≈ 5 km/h).
- **Bike lanes:** Significant effect overall ($F=6.011$, $p<0.001$), but category contrasts are mixed/marginal: Roads with no bike lanes tended to have lower speeds compared to those with separated bike paths ($B=-5.919$, $p=0.054$). No significant difference in speeds were found between roads with bicycle gutters and roads with separated bike paths.
- **Lane width:** Significant, positive association ($F=5.492$, $p=0.019$); each additional meter corresponds to a 1.8 km/h increase.
- **Road surface:** Marginal overall effect ($F=2.504$,$p=0.083$); category contrasts show mixed effects: Brick surfaces associated with lower speeds compared to grey asphalt ($B=-2.470$, $p=0.029$). Dyed asphalt showed no significant effect.
- **One-way & on-street parking:** No significant effects.

Overall model fit was meaningful but left ample unexplained variance ($R^2=0.212$), consistent with the complex, context-dependent nature of driving behaviour.

Table 3. GLM Tests of Between-Subjects Effects.

Road characteristic	F-value	p-value
Speed limit	24.912	<.001
One-way street	0.293	0.589
Lane markings	7.207	0.007
Road surface	2.504	0.083
Bike lanes	6.011	<.001
On-street parking	0.543	0.462
Lane width	5.492	0.019

Table 4. GLM Parameter Estimates.

Predictor	B	SE	t-value	p-value
Intercept	39.419	3.836	10.275	<.001
Speed limit (30 km/h)	-7.595	1.522	-4.991	<.001
One-way street (No)	-0.854	1.579	-0.541	0.589
Lane markings (No)	5.028	1.873	2.685	0.007
Road surface (Brick)	-2.470	1.127	-2.191	0.029
Road surface (Dyed asphalt)	-0.516	1.975	-0.261	0.794
Bike lanes (None)	-5.919	3.071	-1.927	0.054
Bike lanes (Gutter/none)	-7.124	3.748	-1.901	0.058
Bike lanes (Gutter)	0.390	2.570	0.152	0.879
Bike lanes (Gutter/separated)	-3.035	3.421	-0.887	0.375
On-street parking (No)	-1.225	1.662	-0.737	0.462
Lane width	1.835	0.783	2.343	0.019

Model Summary: $R^2 = 0.212$, Adjusted $R^2 = 0.197$, $F = 14.189$, $p < .001$

4.4 Perceived safety

OLR results show that perceptions of safety vary by speed context:

- **Below 30 km/h:** Wider lanes and absent lane markings are associated with lower odds of rating a scenario as safer (OR ≈ 0.35, p ≈ 0.049; OR ≈ 0.24, p ≈ 0.047; respectively). Roads without bike lanes show higher perceived safety (OR ≈ 37.9, p ≈ 0.043), suggesting respondents equate minimal modal mixing cues with calmer settings at very low speeds (Table 5).

- **At 30 km/h:** Only street operation mattered: Bi-directional roads had ~46% lower odds of higher safety ratings ($p \approx 0.041$). Asphalt trended towards higher safety (near-sig) (Table 6).
- **At 50 km/h:** Asphalt is associated with much higher perceived safety ($OR \approx 7.48$, $p \approx 0.007$). Any departure from fully separated bike facilities (none/gutter/mixed) is associated with lower safety perception (several effects significant) (Table 7).

Overall, respondents appear to reward designs that visually match the intended speed limit: Tighter, less formalized cues at 30 km/h vs. clearer separation and smooth surfacing at 50 km/h.

Table 5. OLR results of safety perception below 30 km/h.

Road Characteristic	B Coefficient	Odds Ratio	p-value
Lane width	-1.062	0.346	0.049*
One-way street (no)	0.049	1.050	0.892
Lane markings (no)	-1.448	0.235	0.047*
Road surface (asphalt)	-1.518	0.219	0.117
Bike lanes (none)	3.634	37.864	0.043*
Bike lanes (gutter)	2.740	15.487	0.072
Bike lanes (mixed gutter/separated)	3.141	23.127	0.080

Table 6. OLR results of safety perception at 30 km/h.

Road Characteristic	B Coefficient	Odds Ratio	p-value
Lane width	0.271	1.311	0.564
One-way street (no)	-0.619	0.538	0.041*
Lane markings (no)	0.476	1.610	0.491
Road surface (asphalt)	1.604	4.973	0.065
Bike lanes (none)	-2.263	0.104	0.162
Bike lanes (gutter)	-2.001	0.135	0.143
Bike lanes (mixed gutter/separated)	-2.334	0.097	0.158

Table 7. OLR results of safety perception at 50 km/h.

Road Characteristic	B Coefficient	Odds Ratio	p-value
Lane width	0.359	1.432	0.370
One-way street (no)	-0.563	0.570	0.053
Lane markings (no)	-0.124	0.883	0.825
Road surface (asphalt)	2.012	7.480	0.007*
Bike lanes (none)	-3.670	0.025	0.007*
Bike lanes (gutter)	-2.501	0.082	0.032*
Bike lanes (mixed gutter/separated)	-3.251	0.039	0.019*

4.5 Perceived speed limit credibility

OLR results show that credibility perceptions also flip with speed context:

- **30 km/h credibility:** Asphalt surfaces are less credible (OR ≈ 0.144, p ≈ 0.028). Absence of bike lanes often increases credibility (OR ≈ 29.1, p ≈ 0.029), with gutter/mixed configurations showing positive, near-significant trends. Lane width trends negative (wider → less credible), lane markings and one-way not significant (Table 8).
- **50 km/h credibility:** Asphalt surfaces are more credible (OR ≈ 6.02, p ≈ 0.017). Absence of bike lanes reduces credibility (OR ≈ 0.064, p ≈ 0.042), with mixed configurations also reducing credibility (near-sig). Lane width, markings, and one-way are not significant (Table 9).

Perceived credibility is aligned with the "speed reading" of the environment: Brick surfaces and absent bike lanes cue 30 km/h, while asphalt surfaces and clear bike lane separation cue 50 km/h. These perception effects mirror measured V85 speed patterns, consistent with literature linking road appearance, perceived speed limit, and chosen speed.

Table 8. OLR results of 30 km/h speed limit credibility perception.

Road Characteristic	B Coefficient	Odds Ratio	p-value
Lane width	-0.812	0.444	0.081
One-way street (no)	-0.207	0.813	0.559
Lane markings (no)	0.046	1.047	0.941
Road surface (asphalt)	-1.935	0.144	0.028*
Bike lanes (none)	3.371	29.070	0.029*
Bike lanes (gutter)	2.371	10.710	0.080
Bike lanes (mixed gutter/separated)	3.062	21.357	0.053

Table 9. OLR results of 50 km/h speed limit credibility perception.

Road Characteristic	B Coefficient	Odds Ratio	p-value
Lane width	0.107	1.113	0.787
One-way street (no)	-0.435	0.647	0.143
Lane markings (no)	-0.443	0.642	0.432
Road surface (asphalt)	1.795	6.018	0.017*
Bike lanes (none)	-2.753	0.064	0.042*
Bike lanes (gutter)	-1.621	0.198	0.165
Bike lanes (mixed gutter/separated)	-2.354	0.095	0.090

5. Discussion

This study unites objective and perceptual evidence to show why the use of speed limit signage only (without any physical road design intervention) would make the implementation of GOW30 ineffective: In typical Dutch urban settings, drivers exceed 30 km/h unless the environment "tells" them not to. The directionally consistent effects across speeds and perceptions, particularly for road surfacing and the presence and configuration of bike lanes, support the self-explaining roads paradigm. The conceptual model and prior work (e.g., Yao et al.; Ambros et al.) place risk perception as the bridge between design and credibility: When design elements suggest low complexity/low risk, drivers diminish the credibility of a low speed limit. When these elements heighten perceived risk/complexity, lower limits feel legitimate and are more likely to be obeyed.

5.1 Design implications for GOW30

- Use primarily brick surfacing on GOW30 roads. Avoid the use of standard grey asphalt unless offset with strong (visual) narrowing and other rigid cues.
- Provide visual narrowing and expand the use of longitudinal/edge markings to make 30 km/h intuitive. Manage the use of one-way streets with caution as they increased speeds at 30 km/h.
- Prioritise separated bike lanes and gutter-type lanes on higher-speed streets, as they typically read as "room to go faster". For 30 km/h contexts, shared road use can read as "low-speed" but must be carefully managed for actual safety.
- Avoid mixed or shifting treatments along a segment as inconsistency dilutes credibility. Ensure adjacent links/junctions reinforce the same speed message for network-level coherence.

5.2 Limitations and Future Research

Some limitations of this study include: (i) The GLM's relatively low R^2 underscoring unobserved influences (such as traffic mix, level of enforcement, behavioural and temporal factors); (ii) survey perceptions are scenario-based and sample-bounded (n=83); (iii) V85 speed comparisons across different streets with different designs, rather than before-and-after comparisons on the same set of segments; (iv) reliance on Telraam citizen sensors, which are prone to inaccurate or faulty measurements due to their placement or adverse weather conditions; and (v) sample imbalance in some predictor variables (e.g., on-street parking), leading to potential bias in effect sizes and some p-values (e.g., lane markings at 30 km/h). Future research could (i) expand samples and cities to a broader European or international context; (ii) integrate before-and-after speed measurements for redesigned streets to better determine true redesign effects; (iii) test multiple interactions between road design predictors to better understand effect combinations; (iv) pair perceptions with naturalistic driving data or simulations to triangulate credibility mechanisms; and (v) include traffic performance metrics to balance flow and safety in GOW30 designs.

6. Conclusion

GOW30 credibility is highly intertwined with and dependent on self-explaining road design. This study shows that specific design choices consistently shape both actual speeds and the perceived appropriateness of 30 vs. 50 km/h speed limits. The use of brick surfaces, lane markings, narrow lane widths, and the absence of bike lanes reduced speeds and increased the perceived legitimacy of a 30 km/h speed limit. Sign changes alone are insufficient: Credibility requires embedding self-explaining principles into GOW30 road design, which can substantially improve compliance and safety, and ultimately support Vision Zero aims while maintaining an efficient, human-centred street network.

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