Investigation of Urban Rail Crossing Safety in The Netherlands

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Submission date: April 22, 2022

Abstract

In this study, a statistical model is developed for urban rail level crossings using a variety of variables related to infrastructure, traffic and environment. These variables are collected for all separated urban rail lines within the four urban rail networks in the Netherlands, resulting in 666 crossings. Between January 2014 and December 2021, 257 accidents were registered on these crossings where urban rail vehicles were involved. Descriptive statistics show differences in the design of level crossings and that no standard design is applied. Negative binomial regression modelling identifies significant variables that influence safety on crossings. The model shows several significant variables that can explain the occurrence of accidents on these crossings. Sensitivity analyses were conducted to investigate the model's explanatory power. A prediction model is created for a scenario analysis using Safety Performance Functions, which are adjusted by Crash Modification Factors. This prediction model can proactively assess crossings by predicting the number of accidents and assessing safety measures. The scenario analysis focuses on a tram line within Utrecht, the Netherlands, and evaluates three scenarios for improving the safety level of level crossings. Finally, a cost-benefit analysis is created in which costs of measures and accidents are combined. The lowest accident rates can be established by applying boom barriers to crossings, which is even more cost-effective than the doing nothing scenario depending on the type of boom barriers being implemented. Furthermore, decreasing speed on crossings lowers the accident rates; however, this effect is moderate compared to the application of barriers.

Keywords: Empirical Bayes Method, Level Crossing Safety, Negative Binomial Regression, Safety Performance Functions, Urban Rail.

1. Introduction

Cities are struggling with increasing mobility, accessibility challenges and environmental issues. Urban rail is an economical and environmentally friendly way of providing a solution to these challenges through its large transport capacity, high level of comfort and low emissions (Fouracre et al., 2002) (Cliche & Reid, 2007). Urban rail has different forms, e.g., tram, metro, and light rail, which can be defined as a combination of both metro and tram. Urban rail systems have lower safety requirements than conventional rail lines due to their lower speed. However, urban rail systems have many on-grade level crossings where heavy vehicles mix with traffic. Particularly at these locations, there is interaction with vulnerable road users such as cyclists and pedestrians. This research will focus on the level crossing safety of four urban rail systems in the Netherlands, in which only crossings at separated tracks are taken into account.

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Between 2014 and 2021, 257 urban rail involved accidents were registered in the SWOV (Scientific Road Safety Research Foundation) database, leading to ten fatalities, sixty-four injuries, and 183 damage only accidents (SWOV, 2021). Four significant accidents have occurred on level crossings since the new tram line in Utrecht was opened again after refurbishment in early 2021. These accidents led to several injuries, major disruptions, derailments and total damage of more than five million euros (Province of Utrecht, 2021). The number and severity of urban rail involved accidents are not in line with 'Vision Zero', in which the European Union set the target of no serious injuries and fatalities by 2050 (European Commission, 2020). However, from the literature, research related to urban rail safety within the Netherlands is limited, even though that accidents regularly occur between urban rail vehicles and other motorised vehicles, pedestrians, and cyclists. 'Vision Zero' states that infrastructure contributes more than 30% to accidents and that a proactive assessment should be executed instead of traditional reactive measures (European Commission, 2020).

The number of accidents is limited because of the few systems in the Netherlands, although these accidents can be severe. However, in-depth research on accidents at urban rail lines is lacking. Furthermore, there is no overarching policy that investigates accidents, which can also be related to the fact that different urban rail systems exist within the Netherlands, and various organisational forms exist for the different systems. Also, it follows from the laws and regulations that responsibilities are diverse, and each city is responsible for its area of interest. Because no overarching research is carried out, it is unclear whether specific characteristics of urban rail level crossings contribute to unsafety. Therefore, the main research question of this study is: *'What are the effects of factors associated with traffic, environment, and infrastructure on the safety level of urban rail level crossings in the Netherlands?'*

Corresponding sub-questions to guide the research have been formulated, related to the variables which should be included, which characteristics influence safety on level crossings, which countermeasures can be applied and how countermeasures perform in terms of cost-effectiveness:

1. 'What explanatory variables can be included in the statistical model?'

2. 'Which characteristics of level crossings contribute to low or high rankings of the safety level?'

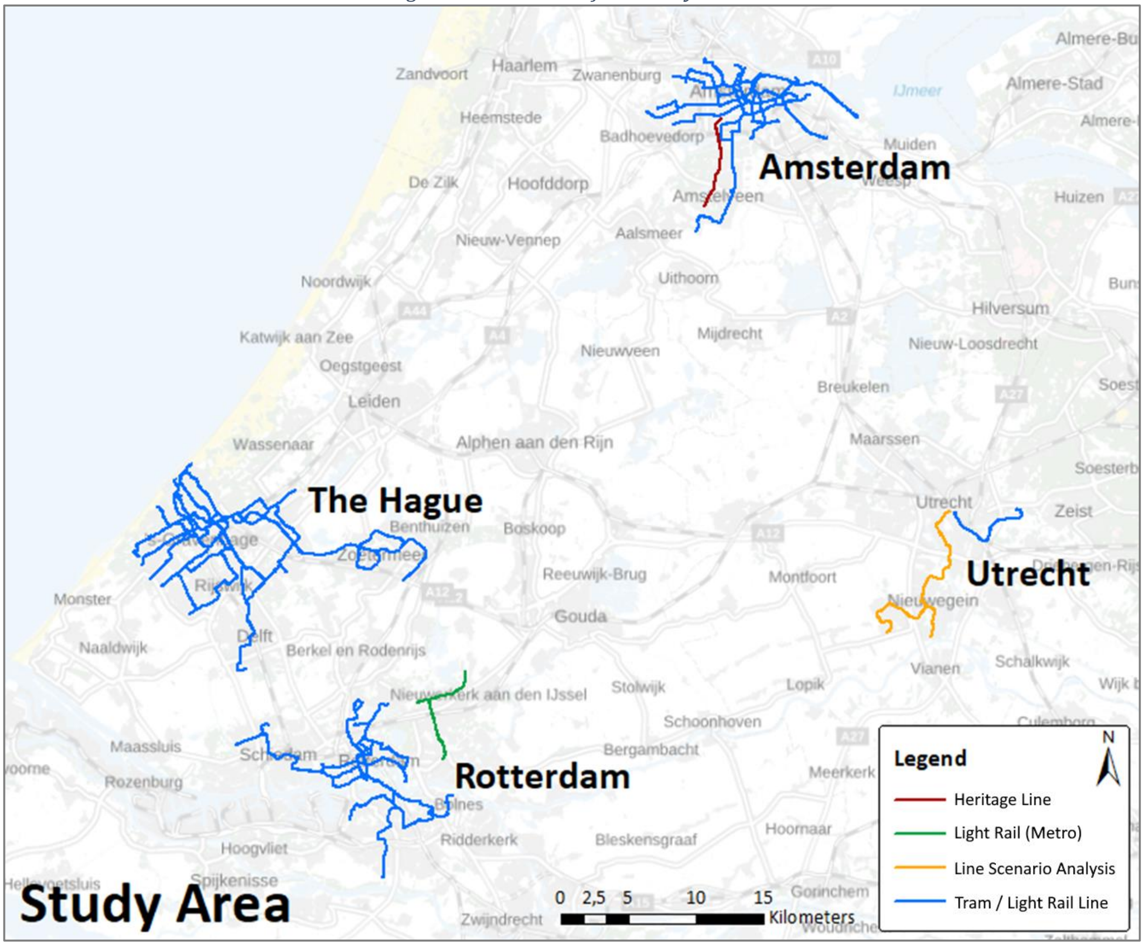
3. 'Which countermeasures can be applied to improve level crossing safety?'

4. 'How do countermeasures perform in terms of cost-effectiveness?'

Since every system is unique, only the Netherlands' urban rail systems will be considered. A map of the research area can be found in Figure 1. Different scenarios to improve the safety level of level crossings were analysed using the developed models for the Utrecht-Nieuwegein/IJsselstein (SUNIJ) tram line in Utrecht, the Netherlands. This tram line is located in the municipality of Utrecht and the neighbouring municipalities IJsselstein and Nieuwegein, which can be considered as satellite cities of Utrecht. The urban rail system of Utrecht is mainly separated from the road network, but a substantial number of level crossings are present in the city.

This research examines the characteristics of level crossings on urban rail lines. It considers how the level of safety can be improved, which is of societal relevance because it explores how accidents numbers at these locations can be reduced. In the state-of-the-art literature, limited research has been executed on this subject while accidents occur regularly, resulting in damages, injuries and fatalities, leading to high social costs. With a better understanding of characteristics that contribute to accident rates, appropriate measures can be taken to reduce the number of accidents and social costs.

Figure 1: Overview of the study area.



2. Background and Literature

This section discusses the background and literature related to rail crossing safety. In Appendix I, a more extensive literature review can be found, covering additional topics related to the subject.

2.1 Literature Review

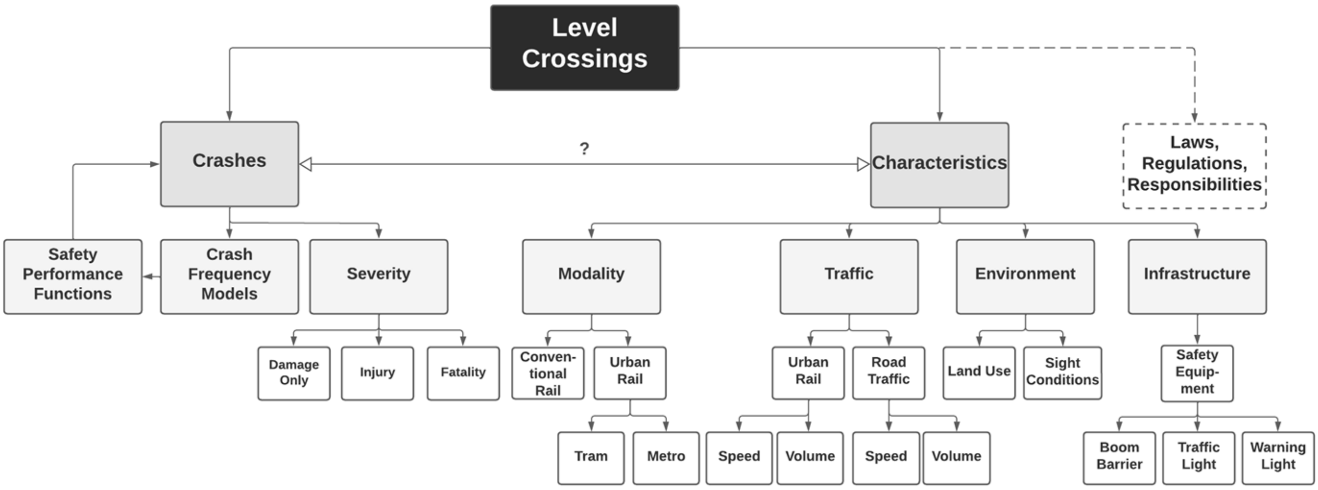
Research has been explored on factors influencing level crossing safety. For the city of Toronto, public transit crash frequency on signalised intersections was explored using a negative binomial (NB) crash prediction model (Shahla et al., 2009). They found that annual average daily traffic, public transit volumes, and traffic volumes have significant relations with public transit-related collisions. An Australian study conducted in Melbourne showed that the higher speed of the urban rail line has a significant relationship with the number of collisions and injuries. A regression model was applied to analyse crash frequency data. Also, other factors influenced the urban rail-involved crash frequency. It is found that when tram service frequency or the tram route section length increases, the number of accidents also increases. Furthermore, increasing traffic volume leads to more accidents. When a tram has lane or signal priority, the number of accidents decreases (Naznin et al., 2016). The same authors conducted another study, focusing on vehicle, road, environment, and driver-related factors (Naznin et al., 2016). The results showed that low floor trams, old trams, tram priority lanes and higher speeds of trams result in significantly more tram-involved fatal crashes. Higher traffic volumes decrease the number of fatal crashes. Fewer accidents happen in residential areas compared to business areas. Also, tram driver characteristics were explored. It is shown that younger tram drivers have fewer fatal crashes than older tram drivers. (Liang et al., 2018) developed an accident prediction model, which highlights the influence of impacting parameters. It was shown that the accident risk is increased with a higher railway speed limit and daily rail traffic. (Read et al., 2021) conducted a systematic review of factors that influence risk at rail level crossings. Eighty-eight studies were reviewed, and a framework was developed for the factors. The factors were split into three categories. The four most identified factors for the category rates and severity of crashes were safety/warning devices, train speeds, road features, and road vehicle speeds. Most of the factors are related to level crossings' physical characteristics and surroundings. Also, the behaviour of road users on level crossing influences risks at level crossings. A study in the Netherlands revealed that several built environment factors impact traffic safety, such as density, diversity, land use characteristics, and road network design (Asadi et al., 2021). (Tasic & Porter, 2016) showed that higher density areas lead to higher accident frequency.

Specific to the Netherlands, limited research has been executed on urban rail safety. In 1998, a working group was formed by the State Traffic Inspectorate, municipalities and transport companies to investigate the safety of urban rail level crossings (Walta et al., 1998). They found that traffic lights secure many level crossings but that these are often designed from the municipalities' own understanding and that more insight is needed into various safety aspects. In 2000, the Transport Safety Board conducted research on the tram and light rail within the Netherlands (Transport Safety Board, 2000). They concluded that legal requirements imposed on transport companies and the special priority status of the vehicles are not in line with the risks and safety issues and that an independent assessment of safety aspects related to infrastructure should take place at the design stage. In 2003, the Transport Safety Board conducted more specific research on separated urban rail tracks (Transport Safety Board, 2003). They found that a separated urban rail track at level crossings creates ambiguity about how road users should behave. It has been recommended that a uniform guideline should be established for the layout of tracks and level crossings. In 2008, research was conducted on the recommendations from the studies above (Stoop, 2008). The study shows that the number of tram accidents is decreasing and that the accidents are not directly related to the tram's speed. The leading causes of accidents are the inattentiveness of road users and the layout of the tram track. Safety can be improved if measures are not taken after an accident but by proactively determining the consequences. The advice from the report is to conduct proactive and scientific research to identify opportunities for improvement in tram safety, and the infrastructure should be harmonized. Furthermore, the study states that there should be improved cooperation between different companies and the unambiguous application of safety principles. The Dutch Transport Safety Board found for conventional railway lines in the Netherlands that, in relative terms, many accidents happen on unprotected level crossings without barriers in relation to the number of level crossings (Dutch Safety Board, 2018).

2.2 Theoretical Framework

A theoretical framework is elaborated to structure all theories from the literature review, as shown in Figure 2. The literature emerged that several variables related to traffic, environment and infrastructure contribute to accidents on urban rail level crossings. Regarding traffic, it is found that the volume of road traffic, speed of road vehicles, speed of trams and frequency of trams affect the number of crashes. Regarding the environment, it is found that in high-density areas, more accidents occur. Regarding infrastructure, it has been found that unsecured level crossings without boom barriers lead to more accidents. Also, it is found that no standardized urban rail level crossing design is applied in the Netherlands. From the literature, it emerged that other factors could affect crashes, such as drivers' behaviour on crossings, characteristics of tram drivers and characteristics of tram vehicles; however, these will not be discussed in this paper since no data is available related to these factors. The variables can have different effects depending on the severity of crashes. The severity of the crashes varies in three categories: damage only accidents, injuries and fatalities. Crash frequency modelling is applicable for determining the influence of characteristics associated with traffic, environment and infrastructure on the safety level of urban rail level crossings. With these models, Safety Performance Functions (SPFs) can be developed to predict the number of crashes. The literature review discusses laws, regulations, and responsibilities, but these are considered out of scope for this paper.

Figure 2: Theoretical Framework.



3. Data Collection, Preparation and Description

3.1 Data Collection

An inventory of level crossings on separated track urban rail lines in the Netherlands is made. Six hundred sixty-seven level crossings are identified: 533 general level crossings with road traffic and 134 bike and pedestrian-only level crossings. Pedestrian only crossings have been considered out of scope since limited data is available for pedestrian volumes, and the design of such pedestrian-only crossings is similar. In addition, an inventory was made of variables and characteristics of level crossings that are hypothetically expected to influence accidents at level crossings. The variables for the analysis are divided into several categories, which are described in Table 1. In Appendix III.1, the variables for the analysis can be found.

Table 1: Description of categories and variables.

Category	Description
Proximity Facilities	Several types of facilities were selected for the analysis based on the literature (Shahla et al., 2009) (Naznin et al., 2016) (Liang et al., 2018) (Tasic & Porter, 2016). The selected facilities can be seen in Appendix III.1. The facilities were loaded from OpenStreetMap using the query tool 'overpass turbo' and then imported into ArcGIS (OSM, 2021).
Demographics	For demographics, four variables have been selected. The percentage of people from a particular background was considered, and the number of households in the area where the level crossing is located (CBS, 2020).
Environment	The environment category considered the influence of the environment. This included the construction year of the buildings in the area, the number of houses, the density of addresses, the value of the houses, and the mixed-use index (MXI). The MXI examines the diversity in land use in a given area (van den Hoek, 2008) (CBS, 2020) (PBL, 2020).
Level Crossing Characteristics	A total of twelve characteristics were inventoried for the design of level crossings by using 360-degree exterior surveys (Cyclomedia, 2021). The characteristics are related to the physical layout of level crossings, such as the presence of boom barriers or the type of warning system.

Rail Characteristics	Also, characteristics related to rail have been inventoried. For the tram's speed, the length between the stops is determined in GIS and timetable information determines the average speed between stops. The frequency of urban rail lines during peak and non-peak is determined by timetable information (OpenOV, 2021).
Road Characteristics	The average speed on a level crossing is determined with floating car data retrieved from Goudappel[1] (HERE, 2021). Also, other relevant data related to road infrastructure was imported from this data set, such as the function class and speed limit.
Traffic Characteristics	The cycling and road traffic volumes were retrieved from the 'Mobiliteitsspectrum' of Goudappel, in which different data sets related to traffic volumes are collected (Goudappel, 2021). Furthermore, several periods over the day were selected, which were incorporated into the analysis. The volumes are for the year 2018.
Accidents	ViaStat[2] is used to inventory accidents (ViaStat, 2021). For this purpose, accidents involving rail vehicles were selected between January 2014 and December 2021. In addition, each crash record was geo-referenced to the nearest intersection, located within forty meters.

3.2 Selection of Variables

A correlation analysis is executed with the identified variables to identify multicollinearity issues. The correlation analysis can be found in Appendix II. The following factors showed high correlation (>Pearson Coefficient > 0,7, p-value < 0,05): 'cycling/traffic volumes during the morning rush (0,884), day (0,978) and evening rush (0,981)', 'urban rail frequencies for peak (0,973)/non-peak (0,991)', 'road lanes' (-0,858), 'road speed limit' (0,816), 'demographics households' (0,984). A Pearson Coefficient of 0.7 is applied since it is generally considered to be a strong correlation with values above 0,7 (Moore et al., 2013). New variables have been defined to mitigate correlation, which is described in Appendix III.2.

Also, the value of tolerance and variance inflation factor is checked since these values indicate multicollinearity among variables (Midi & Bagheri, 2010) (Kim, 2019). Variables with tolerance lower than 0,1 and VIF higher than ten were removed from the analysis. It was found that variables related to the construction year of houses showed high VIF values and were removed from the analysis. Furthermore, the condition index and variance proportions were examined. If the condition index is higher than fifteen, multicollinearity is suspected. According to (Hair et al., 2013), when two or more variance proportions above 0,9 were found, the variable should be removed from the analysis. The variable 'Road Function Class' showed a high condition index (>30) and several variance proportions above 0,9, so this variable is removed from the analysis.

A tetrachoric correlation is applied to check multicollinearity among binary variables. The Pearson correlation check did not show any correlation; however, this method does not apply to binary variables. For this, the tetrachoric correlation needs to be used (Brown & Benedetti, 1977) (Bonett & Price, 2005) (El-Hashash & El-Absy, 2018). The tetrachoric correlation is determined with Equations 1 and 2.

$$\text{Tetrachoric Correlation } \rho = Cos\left(\frac{\pi}{1+\ \omega}\right) \quad (1)$$

$$In\ which: \omega = \frac{f_{00}f_{11}}{f_{01}f_{10}} \quad (2)$$

The tetrachoric correlation for the binary variables can be found in Appendix II.2. Variables with a correlation above 0,7 or lower than -0,7 are marked in Table 1 in Appendix II.2 and have been removed from the analysis. Some variables show a correlation of -1. This is caused by the fact that if a specific variable was present (1), the other variable was never present (0), so this caused a perfect negative correlation. Table 2 on the next page contains the final set of variables for the statistical modelling part.

[1] Goudappel: Dutch consulting firm in the field of mobility.
[2] ViaStat: Accident monitoring tool.

Table 2: Final set of variables.

Category	Variable
Demographics	Non-Dutch Background
Environment	Number of Houses, Value of Houses, Density Registered Addresses, MXI index
Level Crossing Characteristics	Adjacent Intersection, Barrier[3], Cross Marking, Stop Marking, Skewness, Sight Obstructions, Warning System (Traffic Light, Warning Light, Combination or No Warning), Traffic Island
Rail Characteristics	Average Speed, Daily Intensity, Peak Factor
Proximity Facilities < 150m	Bus Stop, Place of Worship, Restaurant, School, Sports Facility, Supermarket
Road Characteristics	Average Speed, Pedestrian/Bike only (yes/no)
Traffic Characteristics	Cycling Volume 24h, Road[4] Volume 24h, Cycling Peak Factor

3.3 Data Description

A total of 666 level crossings were collected for the analysis. An overview per network can be found in Table 3.

Table 3: Overview of networks and cities.

Network	No. of Level Crossings	City
Amsterdam	111	Amsterdam, Amstelveen
Rotterdam	231	Rotterdam, Barendrecht, Capelle aan den IJssel, Schiedam, Vlaardingen
The Hague	255	The Hague, Delft, Leidschendam, Pijnacker-Nootdorp, Rijswijk, Wateringen
Utrecht	69	Utrecht, IJsselstein, Nieuwegein

Different warning systems are present on the level crossings, as shown in Figure 3. One way to secure a level crossing is by using a traffic light. In the Amsterdam and Utrecht networks, it is found that about half of the crossings are equipped with traffic lights (54,1% and 50,7%, respectively), while in Rotterdam and The Hague, the proportions are lower (15,6% and 24,3%, respectively). Another possibility is to equip the crossing with a warning device, often a flashing yellow or red light with an acoustic signal. More crossings with a warning light are present in the Rotterdam network than in the other networks (61,5%). In the network of The Hague and Utrecht, this is 38,8% and 37,7%, respectively. The Amsterdam network has the least number of warning lights (16,2%). A combination of traffic lights and warning lights is also possible; this is often seen in the Rotterdam and The Hague networks (20,3% and 20,4%, respectively), while it is less common for the networks of Amsterdam and Utrecht (9,9% and 10,1%, respectively). In addition, there are also level crossings that are not secured. In the Rotterdam and Utrecht networks, this is almost non-existent (2,6% and 1,4%, respectively), while this is more common in the Amsterdam and The Hague networks (19,8% and 16,5%, respectively).

Also, the network's physical infrastructure of level crossings is examined, which can be seen in Figure 4. A boom barrier is found more often in Utrecht (30,4%) compared to other networks. In the network of The Hague, only two level crossings have a barrier. In Amsterdam, only a few barriers are found (3,6% of the total number of level crossings). For the Rotterdam network, this percentage is slightly higher (13,4%). The number of fences parallel to the tracks differs per network; this is the highest in the Amsterdam and Utrecht networks and the lowest in The Hague. The number of traffic islands is equal across the different networks (27-30%).

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[3] Boom Barrier

[4] Road Traffic: Motorized Vehicles (Passenger Cars, Mid-Heavy Traffic & Heavy Traffic). Volumes are determined at the crossing with GIS, observation year 2018.

Figure 3: Warning system by network.

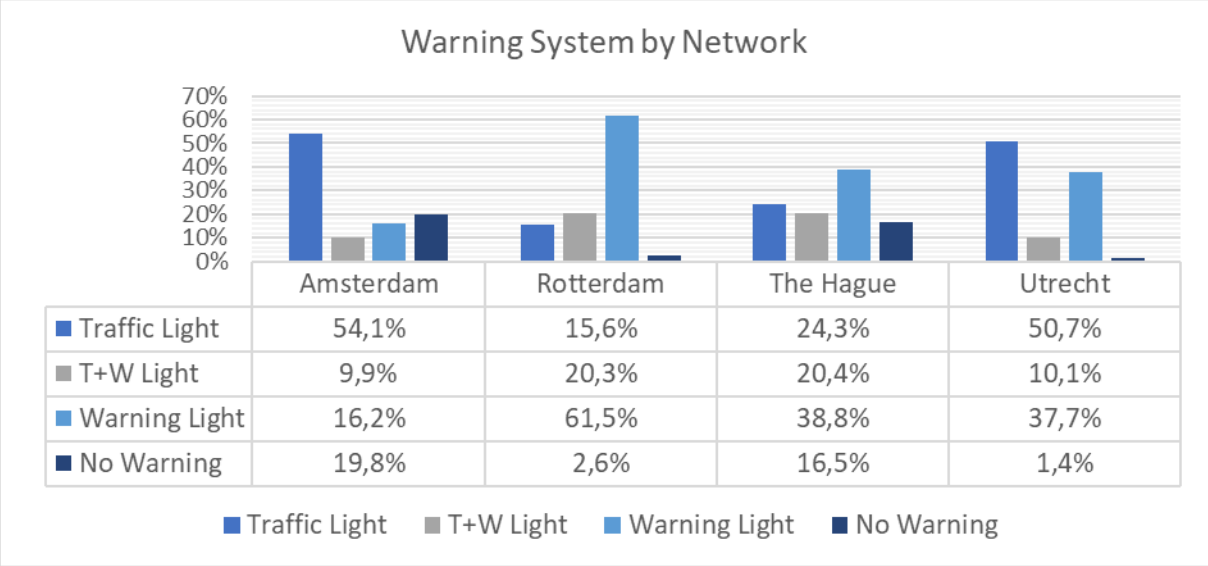
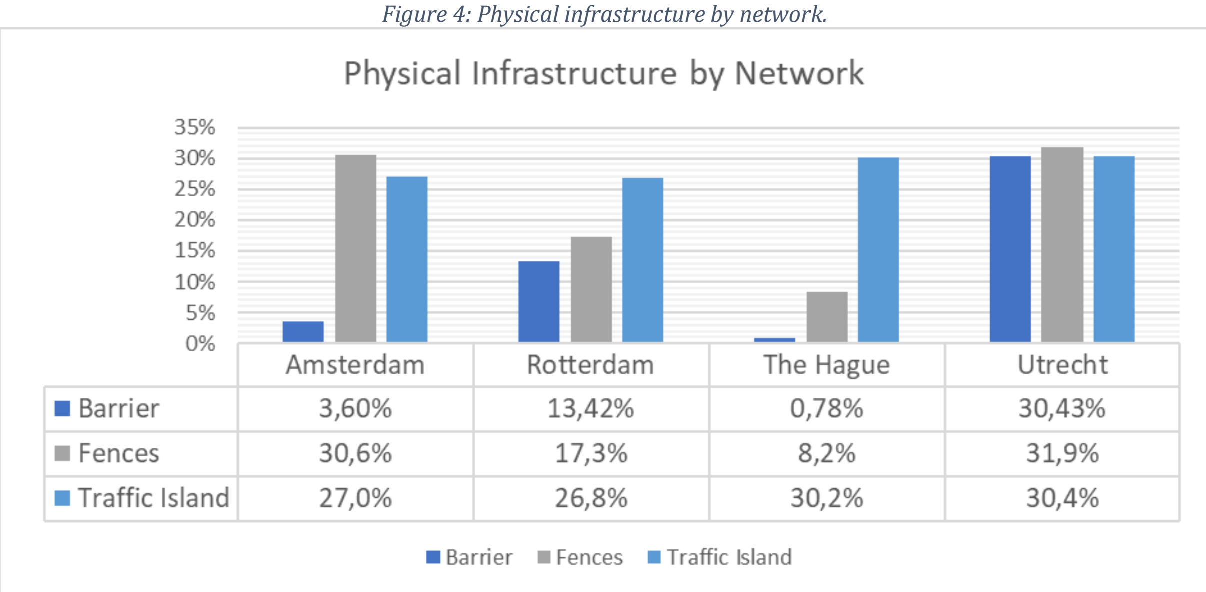


Figure 4: Physical infrastructure by network.



For the 666 level crossings, accident data was collected. Table 4 shows an overview of the accident data.

Table 4: Overview accident data (ViaStat, 2021), observation period: January 1, 2014 – December 31, 2021.

	Min.	Max.	Count	Sum	Mean	Var.	St. Dev.
Total Accidents	0	4	174	257	0,39	0,60	0,78
Accidents (Damage Only)	0	4	136	183	0,27	0,39	0,62
Accidents (Injury)	0	2	59	64	0,10	0,10	0,32
Accidents (Fatality)	0	1	10	10	0,02	0,01	0,12

Figure 5 shows the severity of accidents by the network. It can be seen that the numbers for Rotterdam and The Hague are higher compared to the other cities; however, the network size is also larger. Therefore, the ratio with the number of level crossings has been considered in the next section.

Figure 5: Accident severity by network.

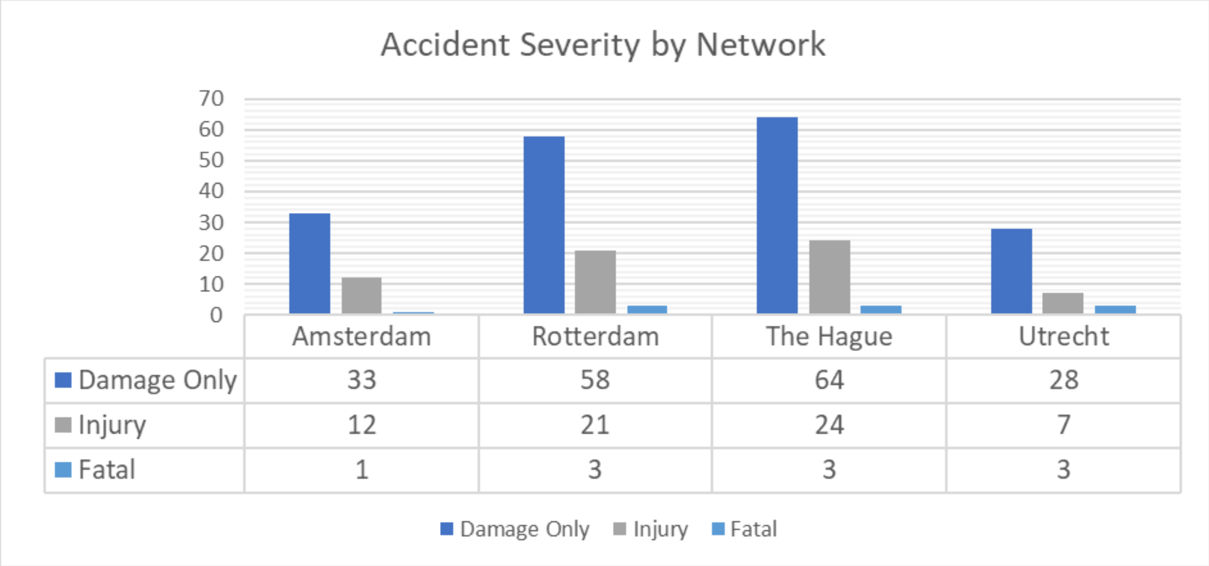
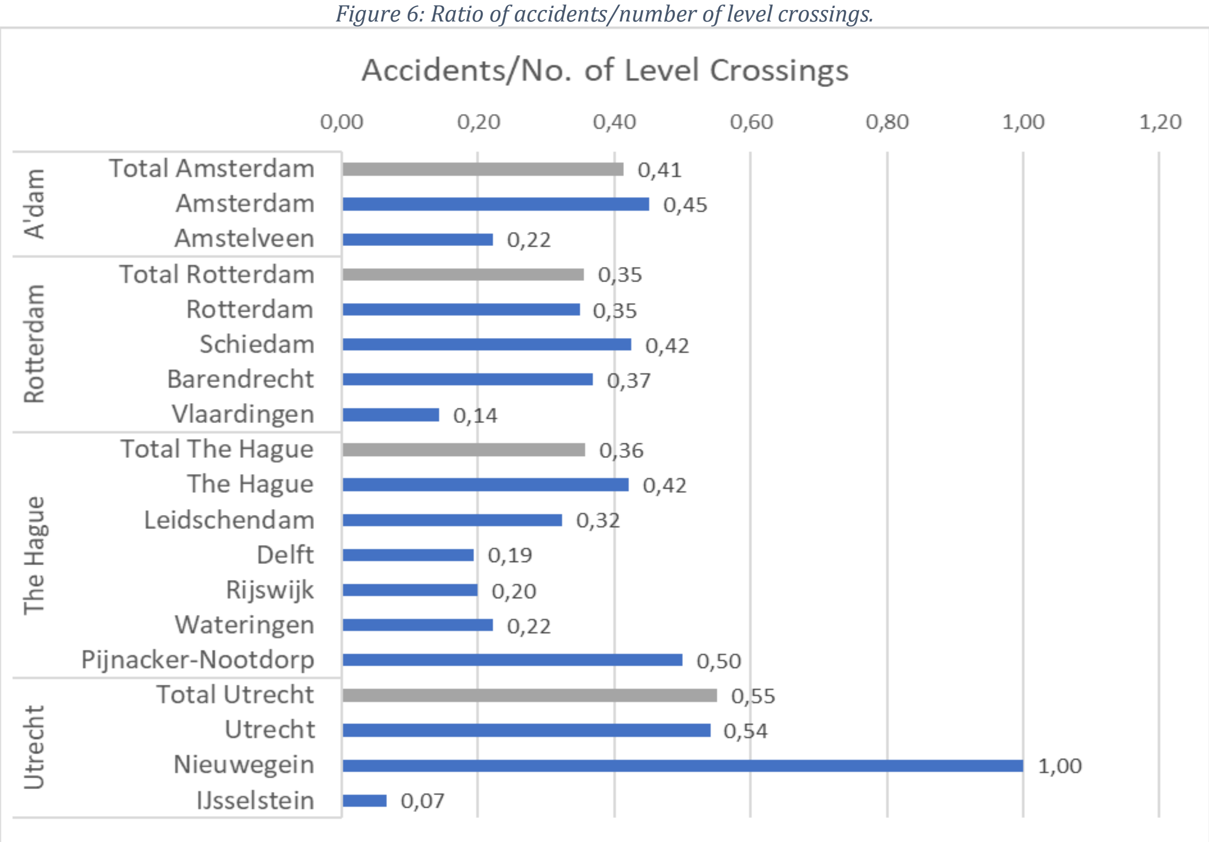


Figure 6 shows the number of accidents plotted against the number of level crossings in the analysis. Here it can be seen that for Amsterdam, Rotterdam, and The Hague, this is primarily the same, but the network of Utrecht has more accidents per number of level crossings. The highest number of accidents per number of level crossings can be seen in the city of Nieuwegein. The lowest number of accidents per number of level crossings is observed in the city of IJsselstein.

Figure 6: Ratio of accidents/number of level crossings.



In Appendix III.3, more extensive descriptive statistics on the data are provided.

4. Methodology

4.1 Statistical Modelling

In the state-of-the-art, a variety of models exist to analyse crash-frequency data. Generally, over-dispersion exists in accident data, which means that the variance is greater than the mean (Hu et al., 2012). Consequently, the estimated parameters may be biased, so a Poisson model is not applicable. However, the negative binomial (NB) regression model can capture the relation between traffic, rail, geometric characteristics, and accident frequency (Hu & Wu, 2008). The NB model can be considered as a generalisation of the Poisson regression model with an extra parameter for the overdispersion. In a Poisson distribution, mean and variance are assumed to be equal, but for the distribution of counts, the variance is not equal to the mean, which implies that crash count data is over dispersed. (Hauer & Bamfo, 1997) (Hauer, 1997). The NB model takes counts as a dependent variable, so the dependent variable is the total number of accidents on a crossing. The NB model is frequently used in crash-frequency modelling (Lord & Mannering, 2010).

For a Poisson distribution, the probability of a crossing i having y_i accidents per year can be seen in Equation 3 (Washington et al., 2010).

$$P(y_i) = \frac{e^{-\lambda_i} * \lambda_i^{y_i}}{y_i!} \tag{3}$$

In which: $P(y_i)$ = *Probability of crossing 'i' having 'y_i' accidents per year.*

λ_i = *Poisson parameter for crossing 'i', which is equal to the expected number of accidents per year, 'E[y_i]'.*

The Poisson Parameter λ_i can be specified as a function of explanatory variables, as seen in Equations 4 and 5.

$$\lambda_i = e^{\beta x_i} \tag{4}$$

$$P(y_i) = \frac{e^{-\lambda_i} * \lambda_i^{y_i}}{y_i!} \tag{5}$$

An extra parameter is added to the Poisson regression model to modify the assumption of equal mean and variance in Poisson distribution, see Equation 6.

$$\lambda_i = e^{\beta x_i + \varepsilon_i} = e^{\beta x_i} + e^{\varepsilon_i} \tag{6}$$

In which: $e^{\varepsilon_i} \sim \Gamma\left(\frac{1}{\alpha}, \frac{1}{a}\right)$

α = *Dispersion parameter.*

To calculate the probability of crossing i having y_i accidents, the negative binomial distribution is applied, as seen in Equation 7.

$$P(y_i) = \frac{\Gamma(y_i + a^{-1})}{\Gamma(y_i + 1) * \Gamma(a^{-1})} \cdot \left(\frac{a^{-1}}{a^{-1} + \lambda_i}\right)^{a^{-1}} \cdot \left(\frac{\lambda_i}{a^{-1} + \lambda_i}\right)^{yi} \tag{7}$$

In which: $P(y_i)$ = *Probability of crossing i having y_i accidents.*

λ_i = *Expected number of accidents on crossing i.*

4.2 Safety Performance Functions

Safety Performance Functions (SPFs) will be developed to generate a predictive accident model for urban rail level crossings. SPFs can be utilised in scenario analysis to assess countermeasures that are not applied yet in reality (Laughland et al., 1975) (Lan & Srinivasan, 2013) (Ghafouri & Bagheri, 2013). For developing

SPFs, the NB model will be applied. This model is preferred since it takes into account counts of accidents. The formula of the SPF can be seen in Equation 8.

$$N_{Count\ Predicted} = e^{b_0 + b_1 * x_{1i} + b_2 * x_{2i} + \cdots + b_k * x_{ki}} \quad (8)$$

Three SPFs are developed in this study: one for all accidents and two severity functions for damage only respectively injury/fatality accidents. The NB model for total accidents and the two severity NB models for damage only and injury/fatality will be reduced to simplify it. Variables that contribute little to no model contribution have been removed in the reduced model. To reduce the model, hierarchical forward with switching selection is applied for a subset selection in the statistical software NCSS. The number of variables was adjusted, considering which number of variables led to the lowest Akaike's Information Criterion (AIC), log-likelihood and Bayesian Information Criterion (BIC). The preferred model is the model with a set of variables that leads to the lowest values of these indices. In addition, some key variables for scenario analysis were considered to be present in the reduced model, based on the author's understanding. These are the urban rail average speed, road average speed and presence of a barrier.
With the SPF for injury/fatality accidents, a ranking is made for the scenario analysis in section 6. Based on this ranking, the top-10 most dangerous locations for the scenario analysis are determined. These locations have the highest number of expected injury/fatality accidents.

4.3 Empirical Bayes method

The Empirical Bayes method (EBM) is used to adjust the predicted number of accidents, following from the SPFs, with the observed accidents in the same time span. The formula for EBM can be seen in Equations 9 and 10 (Hauer et al., 2002). With EBM, the expected accidents are determined for the do-nothing scenario, so when no countermeasures are applied.

$$N_{Expected} = k * N_{Predicted} + (1 - k) * N_{Observed} \quad (9)$$

$$k = \frac{1}{1 + N_{Predicted} * \alpha} \quad (10)$$

In which:
- $N_{Expected}$ = Adjusted number of predicted accidents.
- $N_{Predicted}$ = Number of predicted accidents from NB model.
- k = Weight factor.
- $N_{Observed}$ = Count of accidents that happened at the level crossing.
- α = Dispersion parameter[5] (1/θ).

As described in section 4.1, the NB model can be considered as a generalisation of the Poisson with an extra parameter for the overdispersion. The overdispersion parameter ∝ is used to correct the accident count toward the mean; it accounts for the regression to the mean bias. The standard deviation of the estimate of the expected accident frequency can be found in Equation 11 (Hauer et al., 2002).

$$\sigma\ estimate = \sqrt{\left((1 - k) * N_{Expected}\right)} \quad (11)$$

In which:
- $N_{Expected}$ = Expected accidents from EBM.
- k = Weight factor.

[5] Dispersion parameter α is provided by the statistical software in negative binomial regression modelling.

4.4 Crash Modification Factors

Crash Modification Factors (CMFs) are used to assess the impact of countermeasures and are multiplied by the expected accidents from the EBM to determine the number of accidents. CMFs can be determined by Equation 12 (Gross et al., 2010) (Srinivasan & Bauer, 2013). The predicted crashes by applying a countermeasure can be determined by Equation 13 (Gross et al., 2010).

$$Crash\ Modification\ Factor\ (CMF) = \frac{Safety\ Performance\ Function\ with\ condition\ a}{Safety\ Performance\ Function\ with\ condition\ b} \tag{12}$$

In which: Condition A = With a countermeasure.
Condition B = Without a countermeasure.

$$N_{Expected,with\ countermeasure} = CMF * N_{Expected,without\ countermeasure} \tag{13}$$

The equation for the CMF implies that a countermeasure is already present in the SPF to assess the impact of the countermeasure. Therefore, countermeasures that are not part of the SPFs cannot be evaluated.

4.5 Net Present Value

The application of countermeasures provides costs and benefits. The Net Present Value (NPV) can be applied to determine the present value of all future cash flows, including the initial investments. The NPV is used in a cost-benefit analysis (CBA) to assess the costs and benefits over the lifetime of an investment of a countermeasure. The formula for the NPV can be found in Equation 14.

$$Net\ Present\ Value\ (NPV) = \sum_{t=0}^{n} \frac{R_t}{(1+i)^t} \tag{14}$$

In which: R_t = Net cash flow at time t.
i = Discount rate.
t = Time of cash flow.

4.6 Sensitivity Analysis Variables

Proximity of Facilities

The initial analysis considered the influence of several facilities, as depicted in Table 2, on the number of accidents, observing a distance of 150 meters. However, as shown in the literature, different distances are applied for the area of influence of facilities. Therefore, several models were created to examine whether other distances lead to different results. These models included distances of 250 meters, 500 meters and 750 meters of influence area around level crossings. The outcome of this analysis can be seen in Appendix V. The analysis shows that different distances lead to different effects for the areas of influence of facilities on the number of accidents. However, no specific distance emerges that leads to more significant effects. The literature shows that different distances have been used for the area of influence. From this, a distance of 100-150 meters often emerged; therefore, it was decided to use the influence area of facilities of 150 meters in the final model.

Combination of Facilities

The initial analysis examined the individual effects of facilities on the number of accidents. As shown from the results in section 5.1, only the restaurant significantly affects the number of accidents. However, a combination of facilities may lead to significant effects. Therefore, different combinations of facilities within 150 meters from the level crossing were analysed. The results of this analysis can be found in Appendix VI. It can be concluded that combinations of facilities do not result in significant results.

Counts of Facilities

The analysis used a binary variable for the presence of a facility in an area of 150 meters circumference of the level crossing. In addition, a sensitivity analysis was conducted to examine if counts of facilities in this area of influence lead to significant results, which can be found in Appendix VII. This analysis shows that counts of facilities do not lead to significant results.

Analysis of Density Level Crossings

The number of level crossings within specific areas of influence was examined to determine whether they would result in significant effects. For this purpose, the number of level crossings within areas of 150 meters, 250 meters, 500 meters and 750 meters was determined. A correlation analysis was performed, showing that no significant correlations were found. Subsequently, several models were created with the different areas of influence and the number of level crossings. The outcome can be seen in Appendix VIII. It is found that the density of level crossings does not lead to significant effects. Therefore, it is assumed that the density of level crossings has no relation to the number of accidents in the study dataset.

Analysis of Traffic Volumes

The initial results found that traffic volumes are not significant in the statistical model. The Mobility Spectrum model by Goudappel was used for the traffic volumes (motorized vehicles). However, it is uncertain whether this model is entirely accurate. Therefore, a sensitivity analysis is applied to the traffic volumes to see if an increase or decrease might impact the results. For this purpose, two analyses have been made, a slight deviation of traffic volumes and a larger deviation in traffic volumes.

For the slight deviation model, 1/3 of the volumes were increased by 15%, 1/3 remained the same, and 1/3 were reduced by 15%. For the larger deviation, 1/2 of the volumes were increased by 50%, and 1/2 were decreased by 50%. Then, this analysis was randomised one hundred times and put into the statistical model. It is shown that the model with a slight deviation (+/- 15%), out of 100 models, was not significant 100 times, which can be seen in Appendix IX.1. Also, it is shown that the model with a larger deviation (+/- 50%), out of 100 models, was not significant 94 times and significant six times ($p < 0,05$), which can be seen in Appendix IX.2. The model with a larger deviation was significant only six times. Therefore, it is concluded that traffic volume does not significantly contribute to the number of accidents on level crossings within the observed dataset. This can be explained by the fact that quiet roads with low traffic volumes have fewer warning systems than roads with high volumes equipped with traffic lights or even additional warning systems such as warning lights or barriers. Although the probability of accidents is lower due to lower volumes, this is mitigated by fewer warning systems being present on the crossing.

5. Results

5.1 Statistical Modelling

A negative binomial (NB) model is applied for statistical modelling, as discussed in section 4.1. The outcome of the statistical software can be found in Appendix IV.1. The NB model has a deviance of 442,6 log-likelihood of -494,7 and AIC of 1049,4. The significant parameter estimates can be seen in Table 5.

Table 5: NB Model, Significant Results, p < 0,05.

Model AS-T	B	Lower C.I.	Upper C.I.	HT Wald Chi Square	Sig.	Exp(B)
Intercept	-4,277	-6,162	-2,392	19,803	0,000	0,014
Barrier = 1	-2,396	-2,966	-1,825	17,640	0,000	0,091
Rail Average Speed	0,041	0,031	0,052	14,516	0,000	1,042
Road Ped./Bike Only = 1	-0,957	-1,256	-0,659	10,240	0,001	0,384
Cycling Peak Factor	1,225	0,686	1,764	5,153	0,023	3,404
Cross Marking = 1	0,486	0,268	0,705	4,973	0,026	1,626
Road Average Speed	0,017	0,009	0,025	4,452	0,035	1,017
Restaurant <150m = 1	0,428	0,225	0,631	4,452	0,035	1,534
Sight Obstructions = 1	0,444	0,222	0,666	4,000	0,046	1,559

Eight variables are significant (p < 0,05). If a barrier (boom barrier) is present at a tram crossing, accidents are significantly lower (p = 0,000) than those without barriers. For the speed of the urban rail vehicle, for every 1 km/h increase in speed, there is an increase in the number of accidents (p = 0,000). Also, it can be seen that at a tram crossing intended only for pedestrians and cyclists, the number of accidents is lower (p = 0,001). When the cycling peak factor (ratio of rush hour volume to 24-hour volume for bicyclists) increases, this leads to more accidents (p = 0,023). It is further found that when cross marking is applied to the road surface, the number of accidents is higher (p = 0,026). Other significant variables are the proximity of a restaurant (p = 0,035), average speed of the road traffic (p = 0,035) and if sight obstructions are present on the crossing (p = 0,046). When a restaurant is present within 150 meters, the number of accidents increases. For every 1 km/h increase in road traffic speed, the number of accidents is increased/ Also, when sight obstructions are present, accidents numbers are higher.

5.2 Severity Models

Besides the model with all accidents, two severity models are developed. One severity model considers damage-only (DO) accidents, and the other includes injury/fatality (IF) accidents.

Damage Only (DO)

The dependent variable in this analysis is the variable' damage-only accidents'. The outcome of the software can be found in Appendix IV.2. The NB model has a deviance of 371,7, a log-likelihood of -390,1 and an AIC of 840,2. The significant parameter estimates can be found in Table 6.

Table 6: NB Model, Damage-Only, Significant Results, p < 0,05.

Model AS-DO	B	Lower C.I.	Upper C.I.	HT Wald Chi Square	Sig.	Exp(B)
Intercept	-5,415	-7,628	-3,202	23,040	0,000	0,004
Road Ped./Bike Only	-1,531	-1,952	-1,111	13,250	0,000	0,216
Rail Average Speed	0,043	0,031	0,055	12,180	0,001	1,044
Barrier = 1	-2,216	-2,866	-1,567	11,628	0,001	0,109
Sight Obstructions = 1	0,591	0,351	0,832	6,052	0,014	1,806
Cycling Peak Factor	1,595	0,943	2,247	6,003	0,015	4,927
Restaurant <150m = 1	0,523	0,294	0,752	5,244	0,022	1,687
LC Warning System 'TLWL'	-0,713	-1,061	-0,365	4,203	0,041	0,490

As shown in Table 6, seven variables are significant (p < 0,05). Compared to the NB model for total accidents, the warning system 'Traffic Light + Warning Light' is significant (p = 0,041). When a tram crossing is intended for 'pedestrians and bikes' (p = 0,000), when a 'barrier' is applied (p = 0,001) or when the warning system 'Traffic Light + Warning Light' is applied (p = 0,041), the number of damage only accidents is lower. Again, the speed of the urban rail vehicle is significant; for every 1 km/h increase in speed, more damage-only accidents take place (p = 0,001). When the 'cycling peak factor' (ratio of rush hour volume to 24-hour volume for bicyclists) increases, this leads to more accidents (p = 0,015). Also, the 'proximity of a restaurant within 150 meters' leads to more damage only accidents (p = 0,022).

Injury/Fatality (IF)

The dependent variable is the variable' injury & fatality accidents', created by combining the counts for injury & fatality (IF accidents). An injury or fatality only model did not show any significant results. The outcome of the software can be found in Appendix IV.3. The NB model for IF accidents has a deviance of 245,5, a log-likelihood of –219,2 and an AIC of 498,5. The significant parameters can be found in Table 7.

Table 7: NB Model, Injury/Fatality, Significant Results, p < 0,05.

Model AS-IF	B	Lower C.I.	Upper C.I.	HT Wald Chi Square	Sig.	Exp(B)
Intercept	-4,264	-7,393	-1,134	7,129	0,008	0,014
Rail Average Speed	0,044	0,027	0,060	6,864	0,009	1,045
Barrier = 1	-2,697	-3,782	-1,613	6,200	0,013	0,067
Cross Marking = 1	0,823	0,472	1,175	5,476	0,019	2,278

Compared to the total accidents NB model and damage only NB model, the injury/fatality model shows less significant variables. Due to the low number of counts for injury/fatality accidents, the model's explanatory power is limited, resulting in fewer significant variables. The 'urban rail average speed', 'barriers' and 'cross marking' are significant variables. Every 1 km/h increase in urban rail average speed, results in more IF-accidents (p = 0,009). When a barrier is present on a level crossing, significantly lower IF-accident numbers are seen (p = 0,013). When a cross marking is applied, the number of IF accidents are increased (p = 0,019).

Overview Models

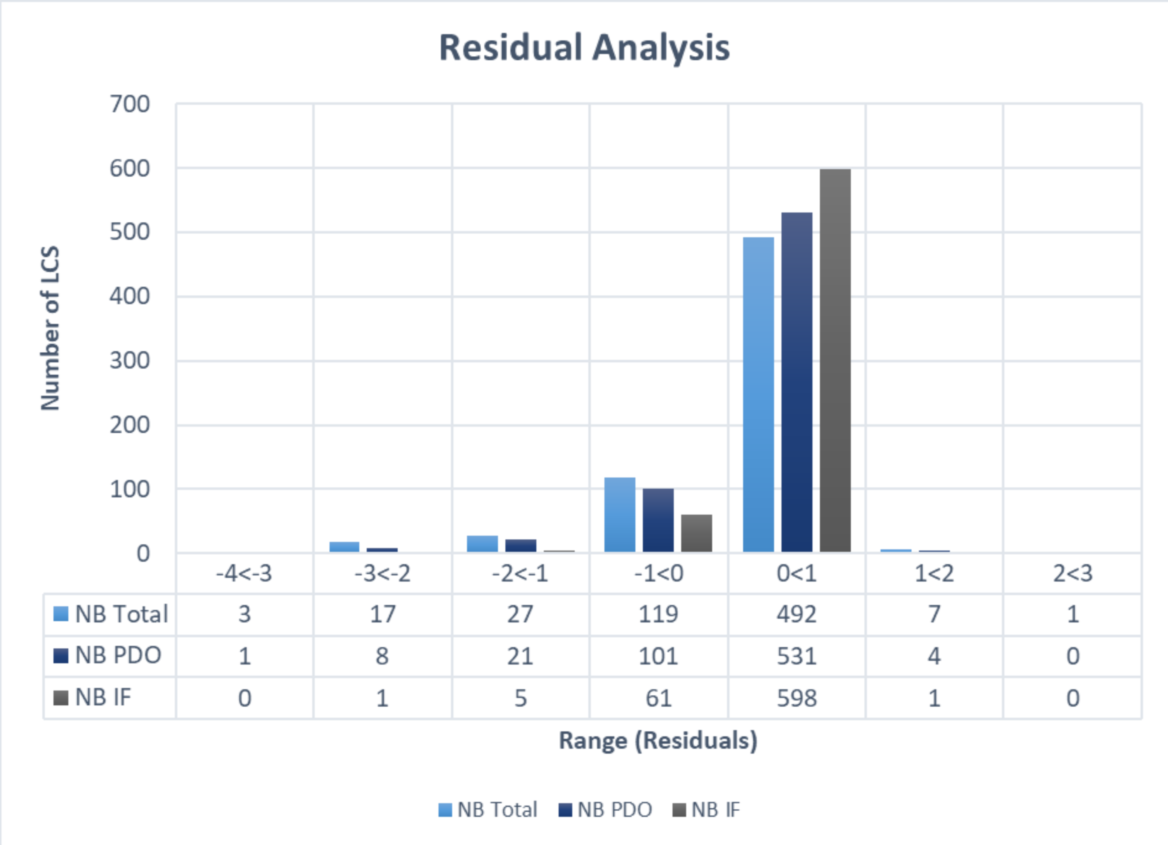
An overview of all variables is provided in Appendix IV.4. It can be found that the 'proximity of restaurant' is significant in the model of the total accidents (p = 0,035) and damage only model (p = 0,022) but not in the IF model. The same is valid for 'sight obstructions'; this variable is significant in the model of the total accidents (p = 0,046) and the damage only model (p = 0,014) but not in the IF model. Also, this can be seen for the variables' pedestrian/bike only' and 'cycling peak factor'. Furthermore, it is found that a 'cross marking' on the road surface is significant for the model of the total accidents (p = 0,026) and IF-model (p = 0,019), but not for the damage only model.

5.3 Residual Analysis

An analysis of residuals is developed to assess the performance of the model. The actual number of accidents per crossing is subtracted from the predicted number of accidents from the models (predicted mean of response), which can be found in Appendix X.1. A plot of the residuals can be seen in Figure 7.
Underpredicting implies that the model predicts fewer crashes than the actual number of crashes. However, all models show a higher proportion of overestimation, so the model expects slightly more crashes than the actual number of crashes. The model of total accidents is the model with the most underpredicting. The injury/fatality model has the least underpredicting, caused by the fact that the number of injury/fatality accidents is relatively small compared to the total number of accidents.
In the initial analysis, one intersection was found in the model with a high outlier residual of -6,74. Further research on this outlier showed that a major infrastructural change occurred at' 5 Mei Plein, Utrecht' within the observation period. Before 2017, a large traffic square was located at this location. Seven out of eight accidents happened before the conversion, which the model could not explain since the new situation

was considered. Since this intersection was converted during the period, it was chosen to remove it from the final analysis.

Figure 7: Overview of residuals NB Regression models.



5.4 Safety Performance Functions

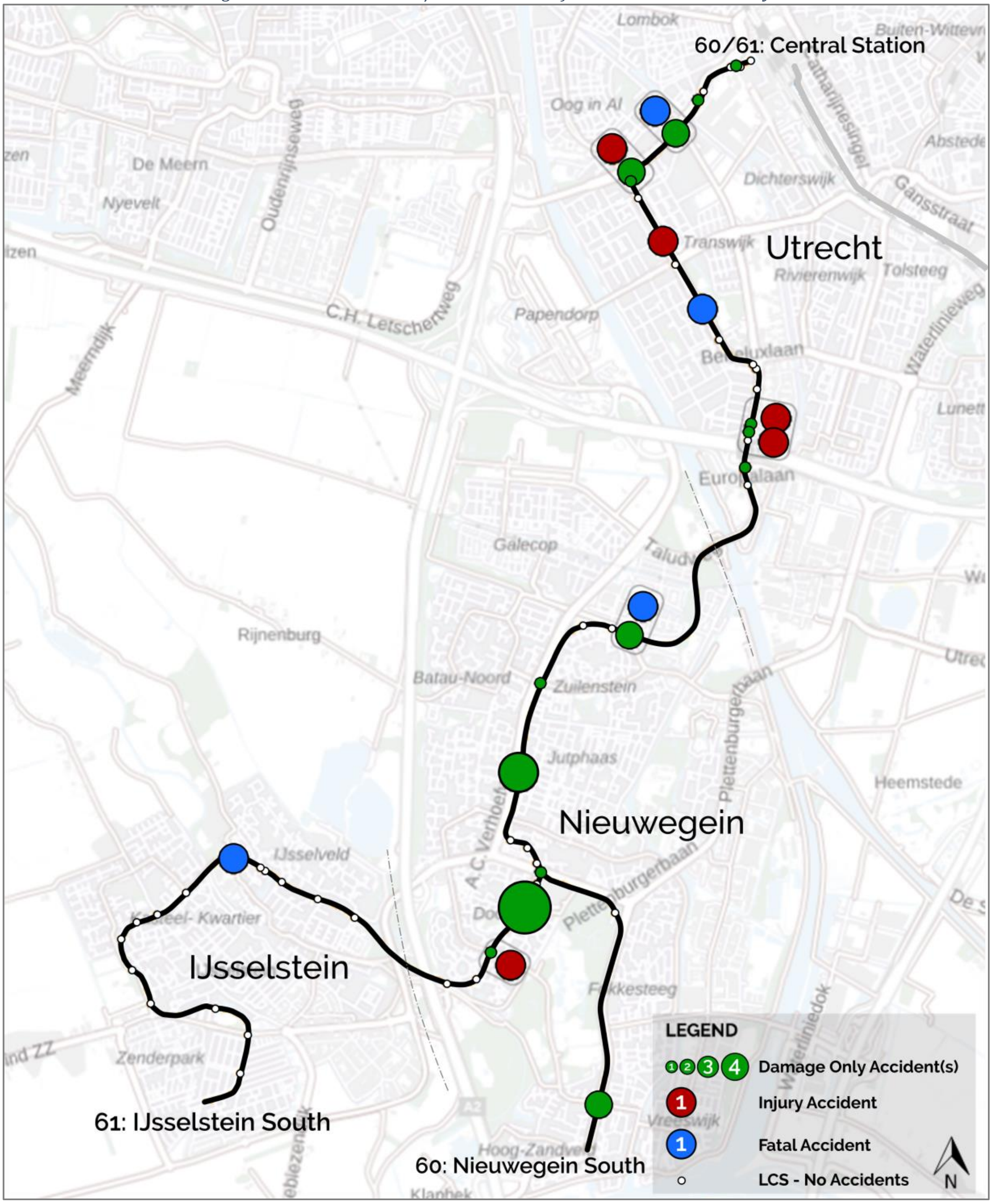
The NB models are used to develop SPFs. The NB models have been reduced by applying the 'hierarchical forward with switching selection' method to lower the number of variables for a simplified model. The models with the lowest AIC, Log-Likelihood and BIC values have been selected. This included checking whether relevant variables for the scenario analysis were included in the model. The equations for SPFs can be found in Table 8. The equation for SPF for total accidents can be found in Equation 15, and the model can be found in Appendix IV.5. The equation for damage only accidents can be found in Equation 16, and the model can be found in Appendix IV.6. The equation for injury/fatality accidents can be found in Equation 17, and the model can be found in Appendix IV.7.

Table 8: Overview of Safety Performance Functions.

Safety Performance Function – Total Accidents	
= EXP(−4,213 + 0,080 * (Density Registered Addresses)$_i$ + 0,487 * (MXI)$_i$ + 0,360 * (Restaurant <150m)$_i$ – 0,465 * (School <150m)$_i$ + 0,502 * (Adjacent Intersection)$_i$ – 2,281 * (Barrier)$_i$ + 0,570 * (Cross Marking)$_i$ – 0,283 * (Skewness)$_i$ + 0,490 * (Sight Obstructions)$_i$ + 0,044 * (Rail Average Speed)$_i$ + 0,018 * (Road Average Speed)$_i$ – 0,996 * (Pedestrian/Bike Only)$_i$ + 1,119 * (Cycling Peak Factor)$_i$)	(15)
Safety Performance Function – Damage Only Accidents	
= EXP(−4,456 + 0,124 * (Density Registered Addresses)$_i$ + 0,490 * (Restaurant <150m)$_i$ – 0,449 * (School<150m)$_i$ + 0,618 * (Adjacent Intersection)$_i$ – 1,989 * (Barrier)$_i$ + 0,604 * (Sight Obstructions)$_i$ + 0,527 * (Traffic Island)$_i$ – 0,331 * (Traffic Light)$_i$ – 0,629 * (Traffic + Warning Light)$_i$ – 0,157 * (Warning Light)$_i$ + 0,045 * (Rail Average Speed)$_i$ + 0,017 * (Road Average Speed)$_i$ – 1,625 * (Pedestrian/Bike Only)$_i$ + 1,287 * (Cycling Peak Factor)$_i$)	(16)

Safety Performance Function – Injury/Fatality Accidents	
$= EXP(-3{,}834 + 0{,}514 * (\text{Place of Worship}<150m)_i - 2{,}727 * (\text{Barrier})_i + 0.664 * (\text{Cross Marking})_i - 0{,}495 * (\text{Skewness})_i + 0{,}044 * (\text{Rail Average Speed})_i + 0{,}018 * (\text{Road Average Speed})_i + 0{,}050 * (\text{Traffic Volume Motorized Vehicles 24h})_i)$	(17)

Figure 8: Overview line 60/61 - Network of Utrecht - scenario analysis.



6. Scenario Analysis

Scenario analysis is conducted to assess three scenarios for modifying level crossings on the tram line Utrecht – Nieuwegein/IJsselstein (SUNIJ, line 60/61). A map of this line, with the accident records for the period 2014-2021, can be found in Figure 8. With the use of Crash Modification Factors (CMF), Safety Performance Functions (SPF) and the Empirical Bayes Method (EBM), the performance of countermeasures in terms of cost-effectiveness will be identified.

6.1 Scenarios

For the scenario analysis, three scenarios are considered, which can be found in Table 9.

Table 9: Overview of the scenario analysis.

Scenario		Variable
Scenario 0: Do-nothing		For this scenario, no measures are applied at the level crossings. Instead, the prediction model identifies the number of accidents when no countermeasures are applied. These accident numbers are transformed into monetary costs. Therefore, this scenario serves as a base scenario to compare the other two scenarios.
Scenario 1: Apply barriers		Scenarios 1A & 1B consider boom barriers at level crossings, as the statistical model shows that this leads to a considerable reduction in accidents.
	1A	Scenario 1A examines the application of barriers at the locations of the top-10 accidents with the highest number of injury/fatality accidents.
	1B	Scenario 1B examines the application of barriers at all level crossings which are currently not equipped with boom barriers.
Scenario 2: Decrease tram speed		Scenarios 2A & 2B consider the decrease in speed of tram vehicles at level crossings that are not equipped with barriers. This measure is currently applied on the Utrecht-Nieuwegein/IJsselstein line, implemented after several derailment accidents in 2021 (Province of Utrecht, 2021).
	2A	Scenario 2A examines the decrease of speed in the locations of the top-10 accidents with the highest number of injury/fatality accidents. The speed on level crossings is lowered to 20 km/h.
	2B	Scenario 2B examines the decrease of speed at all level crossings which are currently not equipped with barriers. The speed on level crossings is lowered to 20 km/h.

6.2. Empirical Bayes Method & Crash Modification Factors

EBM is applied to find the expected accidents for scenario 0: do-nothing. The predicted damage only accidents can be found in Appendix XI.1, and the predicted injury/fatality accidents can be found in Appendix XI.2.

To determine the impact of countermeasures, CMFs are determined. The CMFs are multiplied by the predicted accidents obtained from the EBM to identify the impact of countermeasures. The CMF uses the developed SPFs, obtained in section 5.4. The CMF is determined by dividing SPFs with and without countermeasures, as described in section 4.4. For both scenarios, this can be found in Table 10.

Table 10: CMFs – Scenarios 1 and 2.

			Formula
Scenario 1 Barriers	Damage only	Currently: Equipped with a traffic light. Proposed: add a barrier and a warning light.	$\frac{e^{-1,989*1-0,331*0-0,629*1}}{e^{-1,989*0-0,331*1-0,629*0}} = 0,102 \quad (18A)$
	Damage only	Currently: Equipped with a warning light. Proposed: Add a barrier.	$\frac{e^{-1,989*1-0,331*0-0,629*1}}{e^{-1,989*0-0,331*1-0,629*0}} = 0,137 \quad (18B)$
	Injury / Fatality	Currently: Equipped with a traffic and/or warning light. Proposed: Add a barrier.	$\frac{e^{-2,727*1}}{e^{-2,727*0}} = 0,065 \quad (19)$
Scenario 2 Decrease Speed	Damage only	Currently: Current speed on the crossing. Proposed: 20 km/h.	$\frac{e^{0,045*1}}{e^{0,045*2}} = 0,956\ (for\ 1\ kmh\ decrease) \quad (20)$
	Injury / Fatality	Currently: Current speed on the crossing. Proposed: 20 km/h.	$\frac{e^{0,044*1}}{e^{0,044*2}} = 0,957\ (for\ 1\ kmh\ decrease) \quad (21)$

6.3 Cost-Benefit Analysis

A cost-benefit analysis (CBA) is developed based on the CBA guidance from CPB[6] (CPB, 2013). A CBA combines the costs of countermeasures with the benefits. A discount rate is applied in which the expected costs and benefits in the future are discounted back to the base year over the lifetime. Working Group Discount Rate 2020 of the Dutch Government advises a discount rate of 2,25% for costs and benefits (Dutch Government, 2020). The Net Present Value (NPV) is applied to determine the present value of all future cash flows, including the initial investments.

The damage costs only and injury/fatality accidents are determined in Appendix XII.1. In Appendix XII.2.1, the costs for scenario 1 are determined, the application of boom barriers. In Appendix XII.2.2, the costs for scenario 2 are specified, decreasing the speed of the tram at the crossing. For this, additional travel time is calculated and multiplied by the Value of Time to monetize the additional travel time of passengers.

The application of countermeasures results in fewer predicted accidents since the predicted accidents for the do-nothing scenario are multiplied by CMFs. The number of accidents and the total costs per year for both scenarios can be found in Appendix XII.3.

For both scenarios, a lifetime is set at twelve years since the lifetime of barriers is twelve years, and the costs and benefits have been discounted. The base year of the calculations is set to 2023. Scenario 1 has initial investment costs for the barriers, and every year, there are expected benefits since fewer accidents are expected to occur. For the benefits in scenario 1, no inflation is taken into account because it is not sure how much the costs of accidents will increase in the future (Roelofsen, 2022). For scenario 2, no initial investment costs are calculated, but the additional travel time due to decreasing the speed is monetized by using Value of Time figures from Rijkswaterstaat. Since the Value of Time figures are provided for every decade until 2050, these are interpolated for the years in between to calculate the costs per year. For scenario 2, the expected benefits are the lower number of accidents compared to the do-nothing scenario.

As mentioned before, both scenarios consist of two parts. One part considers applying measures to the top-10 locations with the expected most injury/fatality accidents. The other part considers applying countermeasures on all level crossings. For scenario 1, both the AHOB[7] barriers and VOS[8] barriers are calculated. It is assumed that AHOB and VOS barriers have an equal effect in reducing accident numbers. The calculations for scenario 1 with AHOB barriers can be found in Table 11, and the calculations for scenario 2 with VOS barriers can be found in Table 12. The calculations for scenario 2 with decreasing the speed at level crossings can be found in Table 13.

Table 11: Scenario 1 with AHOB barriers.

Base year: 2023 *Period: 2023-2034 (12 years)* *Discount Rate: 2,25%*	**Scenario 0** **Do-nothing**	**Scenario 1A** **Apply AHOB barriers** **Top-10 IF locations**	**Scenario 1B** **Apply AHOB barriers** **All locations**
No. / Costs IF Accidents / Year	0,80 / € 886.041	0,39 / € 426.459	0,09 / € 93.849
No. / Costs DO Accidents / Year	2,36 / € 853.208	1,46 / € 529.188	0,37 / € 131.958
Costs of Countermeasures	-	€ 8.750.000	€ 29.750.000
Total Costs	**€ 20.837.871**	**€ 20.217.765**	**€ 32.459.680**
Present Value	-	*€ 620.106*	*€ -11.621.809*
Net Present Value	-	€ -405.331	€ -13.633.179

[6] CPB: Dutch Bureau for Economic Policy Analysis.
[7] AHOB: Automatic Half Barrier, see Appendix XII.2.1.
[8] VOS: Safety Support Barriers, see Appendix XII.2.1.

Table 12: Scenario 1 with VOS barriers.

Base year: 2023 *Period: 2023-2034 (12 years)* *Discount Rate: 2,25%*	**Scenario 0** **Do-nothing**	**Scenario 1A** **Apply VOS barriers** **Top-10 IF locations**	**Scenario 1B** **Apply VOS barriers** **All locations**
No. / Costs IF Accidents / Year	0,80 / € 886.041	0,39 / € 426.459	0,09 / € 93.849
No. / Costs DO Accidents / Year	2,36 / € 853.208	1,46 / € 529.188	0,37 / € 131.958
Costs of Countermeasures	-	€ 1.000.000	€ 3.400.000
Total Costs	**€ 20.837.871**	**€ 12.467.765**	**€ 6.109.680**
Present Value	-	*€ 8.370.106*	*€ 14.728.191*
Net Present Value	-	€ 7.344.669	€ 12.716.821

Table 13: Scenario 2.

Base year: 2023 *Period: 2023-2034 (12 years)* *Discount Rate: 2,25%*	**Scenario 0** **Do-nothing**	**Scenario 2A** **Decreasing speed** **Top-10 IF locations**	**Scenario 2B** **Decreasing speed** **All locations**
No. / Costs IF Accidents / Year	0,80 / € 886.041	0,57 / € 632.098	0,47 / € 516.167
No. / Costs DO Accidents / Year	2,36 / € 853.208	1,73 / € 625.897	1,39 / € 503.429
Costs of Countermeasures	-	€ 11.023.749[9]	€ 20.655.025[9]
Total Costs	**€ 20.837.871**	**€ 26.119.688**	**€ 32.890.181**
Present Value	-	*€ -5.281.817*	*€ -12.052.310*
Net Present Value	**-**	€ -4.636.304	€ -10.625.810

As can be seen, scenario 1 substantially reduces the number of accidents compared to Scenario 0. Although the AHOB barriers reduce the number of accidents, the NPV is negative because AHOB barriers have substantial investment costs which exceed the savings from accidents. The VOS barriers show a positive NPV since the investment costs are lower than AHOB barriers. Scenario 2 also lowers the number of accidents; however, scenario 1 shows a greater reduction in accidents. It is found that scenario 2 leads to higher costs than the do-nothing scenario. Lowering the speed results in longer travel time for passengers, which results in additional costs. This effect is low for one trip, but if all the trips in a year are summed, this results in substantial additional costs.

6.4 Sensitivity Analysis

A sensitivity analysis of the CBA is conducted to analyse the explanatory power. A total of four different analyses are prepared for this purpose, which can be found in Appendix XIII. All sensitivity analyses show that scenario 1 with VOS barriers is preferred over the other two scenarios. In scenario 2, the accident number decrease; however, the reduction in scenario 1 is greater.

7. Discussion

In the following sections, the interpretation of the results is discussed, the results are put in a broader perspective, and the research limitations are provided.

7.1 Interpretation of results

The descriptive statistics, data and field study that has been conducted show great diversity in the layout and physical characteristics of urban rail level crossings. Different layouts can be found even within one network or one line. As the literature shows, no overarching design guideline has been established, which results in a great diversity in the layout of tram intersections. Site-specific choices are being made

[9] See Appendix XII.2.2.

concerning the layout, and no policy has been formulated for designing such locations. Accidents involving trams result in major damage, risk of derailment, injuries and fatalities, which leads to high societal costs. That is why it is extraordinary that there is such a wide variety in the design of intersections, even within the same city and line. If a comparison is made with conventional railways, all level crossings throughout the Netherlands are designed in the same way, according to a design guideline.
From the analysis of tram-involved accidents, the ratio of accidents with the number of level crossings for all networks and cities is determined. It shows a variety of proportions between different networks and cities. However, the Utrecht network's ratio is higher than the networks of Amsterdam, Rotterdam and The Hague. Nevertheless, within the Utrecht network, differences in proportions can be seen within the cities in which the network is located. The city of IJsselstein has the lowest ratio of all cities, while Nieuwegein has the highest ratio of all cities. This difference is caused because, in IJsselstein, all crossings are equipped with a barrier, so the accidents numbers are very low. Remarkably, the design of level crossings on the same line between different municipalities is different. Different designs between municipalities on the same line raise the question of who decides and pays when barriers are installed. Since most tram lines run through several municipalities, this should not be a concern for the municipalities. Instead, there should be provincial or national policy.
From the statistical modelling, eight variables turn out to be significant in the model of the total accidents. It is shown that a boom barrier on a tram crossing results in fewer accidents. Also, the speed of a tram is a significant variable, an increase in speed results in more accidents. Furthermore, level crossings for cyclists and pedestrians show fewer accidents; however, underreporting of accidents at these intersections may result in a lower registration of accidents than actually occur on these types of level crossings. The ratio of rush hour volume of cyclists to the 24-hour volume of cyclists shows a significant relationship. More accidents are observed when the rush hour volume is high compared to the 24-hour volume on crossings. Also, it is found that when cross marking is applied on the road surface, more accidents are registered. However, this effect is expected to be caused by additional variables not included in the model, such as the spatial design or the lack of space to line up. Another significant variable is the presence of a restaurant within 150 metres. Also, an increment in speed for motorized vehicles results in more accidents at crossings. Another aspect is sight obstructions in the vicinity of the level crossings, increasing accident numbers. Compared to the theoretical framework, it is shown that road vehicles' speed and trams' speed impact accident rates. No significant results were found for the volume of road traffic and frequency/volume of trams. From the literature, it was found that high-density areas have higher accident rates. Restaurants are mainly located in high-density areas, which is in line with the theory. However, variables related to density such as MXI and density of registered addresses do not show any significant results. Also, additional sensitivity analyses that combined different facilities and considered the density of level crossings do not show significant results. Therefore, it is not possible to ascertain if high-density areas lead to more accidents. From the results, it followed that crossings with boom barriers have fewer accidents, which is in line with the theory.
From the scenario analysis, three different scenarios are established for the Utrecht-Nieuwegein/IJsselstein line within the tram network of Utrecht. It is shown that the application of barriers uniformly leads to the lowest accident rates, and the do-nothing scenario leads to the highest accidents rates. Decreasing the speed on level crossings has a moderate effect on accident rates. Lowering the speed of a tram on a crossing never leads to the lowest overall costs; this is always a trade-off between doing nothing or installing barriers on crossings. The trade-off is between the costs of the barrier installations and the reduction of accidents and thus costs of accidents. The analysis shows that different boom barrier systems can be used: AHOB and VOS variants. With the estimated costs for the boom barrier variants, it is shown that the implementation of the fail-safe AHOB variant has slightly higher costs than doing nothing because these barriers have high investment costs. However, the non-fail-safe VOS variant is cost-effective

for both scenarios: for the top-10 and all locations. When VOS installations were installed at all intersections, costs would be lower than doing nothing and continuing with the current situation. Sensitivity analyses on the CBA show the same results as the initial analysis: applying barriers greatly reduces the number of accidents on crossings, and VOS installations are the most cost-effective.

7.2 Results in a broader perspective

The results of this study are based on the developed statistical model. Therefore, the results depend on the accuracy of this model. Furthermore, any results from the scenario analysis could be different if the statistical model is adjusted or optimised by adding more variables to the model. Accident data from 2014 to 2021 has been applied, and with the Empirical Bayed method, the expected accidents for the next eight years can be predicted. The scenario analysis assumes that these accident rates can be proportionally converted to twelve years for the scenario analysis.

Regarding the CBA for the scenario analysis, the most important uncertainties are the costs of accidents and boom barriers. For the costs of accidents, key figures provided by SWOV are applied. This cost estimation indicates average costs for damage only and injury/fatality accidents. A separate calculation has been made as the costs for tram damage are not included in these average costs. The average tram damage in recent accidents is spread over the total number of accidents. If a tram derails in an accident, the costs are expected to be higher. Research showed that the current trams on the tram line of the scenario analysis have a higher chance of derailing, so the average costs of tram damage in an accident could be higher. For the costs of boom barriers, estimations have been made with experts from the field since limited costs information is available for the Dutch context.

The CBA does not consider any infrastructure repair costs, replacement transport for passengers, additional travel time, and damage to the city's image if an accident occurs. If many accidents happen, users and residents may feel insecure, and the tram will be rated lower. However, if fewer accidents occur, the image may be enhanced, making the product more attractive and leading to more ridership. Decreasing the speed of trams on level crossings results in longer travel times, which could decrease ridership and revenue. Such effects were not included in the analysis. It is expected that countermeasures will be more cost-effective if the aforementioned costs are included in the analysis because the accident costs will be higher.

On the other hand, countermeasures could also lead to external effects which are not captured in the CBA. An average cost is assumed for the costs of barriers; however, costs are likely to depend on the layout and design of intersections. Nevertheless, it may not be feasible to install boom barriers at all locations, even though this would reduce the number of accidents. For example, there is a lack of space to place the barriers. Another issue could be that boom barriers lead to a reduction in the capacity of the crossing, resulting in delay time for traffic. In addition, boom barriers need time to open and close, which results in a longer time when the intersection is blocked than a crossing without boom barriers. Furthermore, the presence of barriers at all intersections can lead to a change in the behaviour of road users, as road users have less attention when passing through an intersection due to the presence of boom barriers and a reduction of awareness of a tram crossing. This change of behaviour has to be considered if only a part of all intersections is equipped with a barrier because it can increase the risk of an accident at other intersections where no boom barrier is installed. Furthermore, road users can be less aware of the situation since they might expect a boom barrier on a crossing with tram tracks. However, the presence of boom barriers may decrease the travel time on the tram line, as a higher speed of the tram is possible. The tram's speed can increase ridership since it would be more attractive to travel with a shorter travel time.

For the number of travellers on the tram line of the scenario analysis, it is assumed that this is the same as the years 2015-2019, so on average, 5.6 million per year. However, the Covid-19 crisis may have affected passenger numbers, temporarily lowering them. The average number of passengers per trip is calculated to determine the additional travel time of passengers. Some line segments could have a higher number of passengers, which could increase the costs, while on the other hand, other segments could have a lower number of passengers, which could decrease the costs. Since passenger numbers for each segment are unknown, it was impossible to conduct a detailed calculation. Furthermore, a conversion of the tramline took place in 2020, replacing old high-floor trams with modern low-floor trams. For this study, it has been assumed that the effects of both tram types are the same. However, the modern trams may lead to a more attractive product, causing enhancement of ridership.

7.3 Limitations and further research

The statistical model developed in this research considers different tram networks in the Netherlands, implying that the model is only applicable to the Dutch context, as other countries might yield different results. The study examined accidents at tram crossings on separated tram tracks only, with tram crossings being 'points' to pass tram tracks at specific places. Characteristics of tram crossings are collected, with some assumptions being made because of the scope of the study. The most important assumptions are the daily number of trams and the speed of the trams on the crossing. For the daily number of trams, peak and non-peak volumes have been summed by assuming rush hour times between 07:00-09:00 and 16:00-18:00. In addition, the daily number of trams could be different because of this assumption, as volumes differ per line and time of day. For the speed of trams, the travel time of the timetable is divided by the section length, which results in an average speed. This approach does not include the time when a tram stops at a stop. It is assumed that, on average, this stopping time is equal, which means that there is no difference from the situation in which the time that the tram stops is included. Data from transit feeds could be used to get more insight into the speed of trams on crossings, but this also raises challenges. Data needs to be extracted for each tram line and every crossing, and the speeds are also expected to fluctuate, for example, per day or time of day.

For the accident data, 'Viastat' is used to collect data about tram-involved accidents from the past years. As many tram-involved accidents as possible were collected from the data, whereby an attempt was made to link accidents without an exact location to an intersection. However, it has not been possible to use all data since the exact location of a part of the accidents is unknown. Also, it could be that not all accidents are registered in the database, which could lead to an under-reporting of accidents. The sample size of this study is 666 tram crossings with 257 accidents. The number of injury/fatality accidents is limited since tram accidents are rare, implying that results from this research allow only for drawing preliminary results. A detailed recording of all accidents within tram networks can improve the safety prediction model as more detailed information about the accidents would be available. In addition, the model could be improved by adding data from drivers on near misses, as these also indicate potentially dangerous locations.

The model shows underprediction at a few tram crossings, where fewer accidents are predicted than happened in reality. The top-10 underpredicted intersections have been assessed and compared in Appendix X.2, and other variables are determined that could be added to the model to increase the accuracy. Adding these variables to the model could be executed in future research. Another aspect for further research is the type of barriers. In this research, two types of barriers have been discussed: the fail-safe variant AHOB and the non-fail-safe variant VOS. The research leads to an interesting perspective that barriers generally reduce the number of accidents and that VOS barriers also result in the lowest overall costs. However, limited information is available on the costs of these barriers, and it is recommended that more research is conducted on these costs. For example, an overview of all the costs involved in these barriers installations can be determined. Also, more research needs to be conducted to deal with the trade-off between an expensive fail-safe AHOB barrier and a cheap non-fail-safe VOS barrier. Nevertheless, VOS barriers could lead to a considerable reduction in accidents at low costs. For instance, existing VOS barrier installations can be observed to determine the number of failures, and risk analysis can be developed to compare fail and non-fail-safe barrier types. This may include whether a driver can be alerted if the VOS system is not functioning to mitigate that such an installation is not fail-safe.

8. Conclusion & Recommendations

This paper explores safety on level crossings where urban rail vehicles and road traffic intersect. For this, negative binomial (NB) regression modelling has evaluated the effects of factors associated with traffic, environment and infrastructure on the safety of urban rail level crossings. Significant variables emerge from the statistical analyses that contribute to safety at level crossings ($p < 0{,}05$). A barrier at a crossing shows that far fewer accidents occur at these locations than at crossings without barriers. It also shows that the number of accidents is lower when a crossing is only meant for slow traffic, e.g., pedestrians and cyclists. The number of accidents is higher when the speed of an urban rail vehicle is higher. This also applies when the peak-hour volume of cyclists is high compared to the 24-hour volume. In addition, the number of accidents is higher at crossings with cross markings on the road surface. The NB model shows that the number of accidents is higher when road traffic speed increases. Also, the presence of a restaurant increases the number of accidents. Furthermore, it turns out that the number of accidents also increases with sight obstructions.

With the NB model, SPFs are developed, which are used to develop CMFs to assess the impact of countermeasures. A distinction is made between damage-only accidents and injury/fatality accidents. With EBM, the accidents can be predicted for the scenario without countermeasures, and a ranking is made, resulting in level crossings with the highest number of damage-only and injury/fatality accidents. By multiplying the accident numbers with CMFs, the number of accidents with countermeasures can be estimated. It is shown that several variables have a significant relationship with the number of accidents on crossings, such as the presence of barriers and the average speed of trams. Three scenarios are evaluated for a tram line in Utrecht for the scenario analysis. It is shown that the scenario with boom barriers decreases the number of accidents and is cost-effective when VOS barriers are applied. Lowering the speed of trams on crossings has a moderate effect on decreasing accident numbers and is not cost-effective. Applying VOS barriers on all level crossings which are currently not equipped with barriers results is the most cost-effective scenario in terms of overall costs.

It is recommended to establish a uniform guideline for the design of tram and light rail level crossings, as applied by conventional railways, to reduce the wide variety of tram and light rail level crossing designs. For this purpose, a trade-off framework can be established that considers which safety measures should be applied, taking into account different variables such as volumes and speeds. A detailed analysis should be included to use barriers at level crossings, and the effects since the potential benefits of accident reduction seem to be great. Furthermore, it is recommended that various tram operators and transport authorities join forces to combine their knowledge and experiences. Such an approach can be part of a risk-based road safety policy, in which the most critical accident avoidance risks are adjusted to achieve the goal of zero road casualties by 2050. For societal relevance, decreasing accident rates is of great importance since accidents have a significant impact and involve high social costs.

Acknowledgements

The researcher wants to thank all colleagues of Goudappel who gave advice, provided data and contributed to the study. In particular, thanks go to the supervisors of Goudappel, who have been of great value to the research. The researcher is very grateful for the input of both supervisors from the University of Twente during the research process.

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