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Implications of trams mixed-operations in urban areas on the safety of vulnerable road users

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Preface

«δῶς μοι πᾶ στῶ καὶ τὰν γᾶν κινάσω»
"Give me somewhere to stand, and I will move the earth"
Archimedes

For 2 years of my life, Delft University of Technology was the place where I was standing. The knowledge I acquired from the courses of my Master of Science program (i.e. MSc Civil Engineering, Track: Transport and Planning), was the tool in order to be able to "move the earth". I learnt new scientific methods and concepts from my Professors, I heard innovative ideas about transport engineering from my Colleagues and I had the opportunity to cooperate with many people from all over the world. In the transport infrastructure of the Netherlands, there are numerous interesting practices that enhance sustainable mobility. During these two years, I wondered again and again how we can implement some of the Dutch transport policies/plans in my country, Greece, or at least how we can make them suitable for the culture of Greek people. The previous questions inspired me to develop a PhD project proposal and continue my journey in the world of scientific research.

At this point, I would like to thank all the members of the thesis committee. Specifically, I am very grateful to my daily supervisor, Dr. ir. Haneen Farah for her support and guidance in all the stages of my thesis. The many Skype meetings we did (had) during this process helped me a lot in order to export significant scientific results about traffic safety and improve the way I present them. In fact, the topic of this thesis was based on her own idea that was further developed by me in the next stages. A very special thanks goes to Prof. Marjan Hagenzieker, who was the chair of the committee. She provided me with enough flexibility in order to be able to complete in Greece, where I was working during the same period, a big part of my thesis project. Her detailed comments in the draft document were crucial in order to improve it after the green light meeting. I would like also to thank Dr. ir. Niels van Oort for giving me the opportunity to discuss the objectives and the methodology of this research project with many experts from around the world. The discussions with Dr. Eleonora Papadimitriou were also important in order to determine the methodological steps of the thesis and to improve the Greek version of the survey form. Special gratitude goes out to Panagiotis Papadimitropoulos from STASY (tram company in Athens), who gave me the opportunity to conduct the survey and organized the entire process, and to the trainers of the tram drivers of Athens, who shared their experiences and motivated the drivers to answer the survey.

I am indebted to my parents, Georgios Tzouras and Alexandra Konstantinidou, for supporting me economically and psychologically in order to finish my studies in the Netherlands. Definitely, it was a very difficult period for us. Their confidence and strength helped me to overcome the numerous problems which came up during this period. Furthermore, in this journey into knowledge, I had a very good fellow traveler, partner in the projects and friend; his name is Cristino Perez Lazaro and he is a very passionate engineer as I am. I learnt a lot from our disagreements or conflicts in some of our projects. Very special gratitude goes out to my cousin, Vicky Liakopoulou, who reviewed with me the entire document, corrected my grammatic and syntax mistakes, and gave me ideas in order to improve my sentences. Last but not least, I would like to thank my "teammates" in Sustainable Mobility Unit of the National Technical University of Athens who did not weigh me down with extra work during the last months of my thesis.

At this point, I will let my research unfold to you, dear reader.

Panagiotis G. Tzouras

Summary

Tram is a sustainable mode of transport, which is able to transform the modern city centers through the various urban regeneration projects that usually come together with it. Tram tracks are often shared with either motorized traffic or pedestrians/cyclists. Indeed, in Amsterdam for example, the tram passes through central pedestrianized zones and squares, where the volume of pedestrians is quite high. As urban planners and transport engineers argue, this kind of designs can reinforce effectively sustainable mobility, because walking, cycling and public transport trips are increased and the traffic problems, which have appeared due to car dominance, are mitigated inside city centers. The lack of available urban space in many cities of the world makes the complete separation of tram tracks almost unfeasible.

In this mixed traffic reality, tram accidents are very rare but severe at the same time. Indeed, the most probable outcome of a crash between a tram and a pedestrian is a severe road injury or a fatality, as some previous studies have noticed. The basic problem is that the rail vehicle requires longer distance in order to brake until standstill and at the same time, its mass is much bigger in comparison with the other urban transport modes, such as buses or cars. Tram driving is really a complex and very demanding task, since the tram driver should run on time, maintain his/her concentration, predict the behavior of other road users and protect the tram passengers from falls inside the vehicle cabin. In addition, tram drivers have to adjust their behavior according to the different characteristics of all the different road environments, which exist along a tram route. On the contrary, pedestrians are unaware of the potential dangers when they are interacting with trams.

In the past, a limited number of studies has attempted to examine tram safety, especially in urban areas, where trams interact with vulnerable road users (VRUs) (i.e. pedestrians, cyclists, disabled people etc.). Subjective notions of traffic safety, that are more connected with the behavior of tram drivers, such as: perceived safety and driving stress, have never been quantified in order to interpret better the challenges of tram drivers in mixed traffic operations. Relevant previous studies have presented statistical trends related with tram accidents; yet, the spatial patterns of tram accidents have never been discussed in the literature. Furthermore, the similarities or the differences between objective and perceived safety have never been examined. This thesis covers all the previously mentioned research gaps in order to explain tram safety problems that especially appear in urban areas, where the flow of trams is mixed with the flow of VRUs. Different perspectives of tram driving safety are considered in this analysis, namely: perceived safety, driving stress and objective safety. By utilizing the knowledge from this in-depth investigation, a list of practical recommendations, which can reinforce tram safety without downgrading system efficiency, is developed.

A stated preferences experiment was conducted for the quantification of subjective notions of traffic safety, like perceived safety and driving stress. In the survey, tram drivers rate perceived safety and driving stress in a 7-point Likert Scale. A fractional factorial design was used for the development of an online methodological tool, i.e. an online form. The explanatory variables of perceived safety were selected to be: alignment type (i.e. the level of separation of tram track from the other traffic flows), the existence of a station or pedestrian crossing, and the volume of VRUs; the explanatory variables of driving stress were selected to be: arrival delay, load of standing passengers, familiarity and perceived safety. The tram network of Athens was used as a study case in the stated preferences experiment; therefore, images from different tram sections of Athens were collected and presented to the respondents (i.e. the tram drivers of Athens). The output of the stated preferences experiment was a set of perceived safety and driving stress ratings. These ordered data points were processed using the proportional odds method (i.e. ordered logit) in order to develop two ordinal models (i.e. one perceived safety model and one driving stress model). The developed models present in statistical terms the level of influence of each of the previously mentioned explanatory variables on perceived safety and driving stress. To describe heterogeneity in preferences among the individuals, random beta parameters were introduced in the perceived safety and driving stress model functions. The estimation of these random beta parameters was accomplished using Simulated Maximum Likelihood (SML) method.

Objective safety is examined in the tram network of Amsterdam using accident records, which were downloaded from BRON database. A Geographic Information System (GIS) was created for this tram network. Spatial data, such as location of stations and pedestrian/cycling crossings, level of tram lines separation, cycling intensity, city attraction poles and city districts, have been imported in the GIS. The spatial patterns of tram accidents were uncovered using black spot analysis. The determination of black spots in the network of Amsterdam was achieved through the estimation of kernel density (KDE) in the 2-D homogeneous euclidean space (planar KDE) and the 1-D network space (network KDE). Weights connected with the accident severity have been imported in the estimation process.

According to the estimated model of perceived safety, alignment types, like: tram/pedestrian malls and mixed traffic operation, downgrade perceived safety. Furthermore, the existence of an unprotected pedestrian crossing and high volumes of VRUs influenced perceived safety negatively. All the previously mentioned parameters were correctly selected to be random; the parameter related with the existence of unprotected pedestrian crossing reported the highest heterogeneity and the one related with volume of VRUs the lowest. Driving stress was affected mainly by arrival delay and load of standing passengers. Route familiarity was an additional important factor, that influences driving stress. Definitely, route familiarity is not a random variable; it means that all tram drivers of Athens agreed that driving stress is increased in unfamiliar sections. In Amsterdam, more accidents per km appeared in tram/pedestrian malls; yet, most of the fatal accidents have occurred in tram tracks that are not shared with other road users (i.e. semi-exclusive alignments). High concentrations of tram accidents were also observed around attraction poles and inside the city center, where the flow of VRUs is quite high. In general, the number of tram-VRU accidents that have occurred in Amsterdam in the decade 2007-2017 is 122 (i.e. 11.09 tram-VRU accidents per year). In 78.69% of these events, there was a severe road injury of a VRU. Lastly, in the tram network of Amsterdam, 7 out of total 11 casualties that were reported in Amsterdam in the time period 2007-2017 were pedestrians.

The existence of many random beta parameters in perceived safety and driving stress confirms the subjective nature of these notions. No statistical significant correlation between these two previous notions was observed in this study; yet, route familiarity influences driving stress significantly. One explanation to this is that experienced tram drivers believe that they are ready to respond properly in a section that they perceive as unsafe, if they are familiar with it. If there is no familiarity, tram drivers lack confidence and therefore driving stress is increased. After comparing the results from the perceived safety analysis conducted in Athens and the ones from the objective safety analysis conducted in Amsterdam, no great differences were reported. Tram drivers of Athens seem to know well that the absence of separation between tram tracks and the space dedicated to VRUs leads to more complex interactions and to much higher probability of severe accidents. Possibly, the discussion about tram safety inside the company and the training seminars/sessions has helped them to be more aware of the potential dangers.

As a practical recommendation, a consistent design of a tram line using the knowledge from the estimated perceived safety and driving stress models is developed for the first time. The perceived safety difference from one section to the other can be used as an indicator to identify design inconsistencies of tram lines. Design inconsistencies can be also identified by collecting tram speed profiles, that describe perfectly the driving behavior, since tram drivers control only the longitudinal moves of the vehicle. Furthermore, driving stress of tram drivers could be quantified better through the use of Photoplethysmogram (PPG) sensors that are able to record the heart rate and the skin response. In general, this study claims that the views, experiences, challenges and feelings have to be discussed more thoroughly in the scientific research about public transport safety. One additional argument to the last opinion is that many researchers of traffic safety and transport engineers are car drivers; but very few of them have ever driven a bus or a tram before in order to understand well enough the daily challenges of public transport drivers.

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1 Introduction

Smarter mobility requires the advancement of sustainable transportation, which in many cities in the world, includes the use of trams and light rails. According to van der Bijl et al. (2018), light rails or light rail systems are able to: 1) improve the effectiveness of the transport system, 2) make the city more efficient, 3) boost the economic development, 4) protect the environment and 5) ensure social equity (five E's concept). Furthermore, the increase of walking and cycling trips inside the urban areas is also an important part of sustainable mobility (Bakogiannis et al., 2017).

SWOV (2011) has found that the number of tram accidents with vulnerable road users or (VRUs) with severe outcomes are twelve (12) times bigger (relative number) in comparison with the number of severe car accidents. In addition, according to the results of Marti et al. (2016) study, the percentages of tram collisions leading to personal injuries or deaths were 89.6% for pedestrians, and 83.1% for cyclists in Switzerland. The main problem is that the rail vehicle requires longer distance in order to brake until standstill and at the same time, its mass is much bigger in comparison with the other transport modes, such as buses or cars. Furthermore, the tram driver is unable to maneuver away in order to escape colliding with an object. Nevertheless, it is not always feasible to provide a complete separation of tramways from the other road users (Marti et al., 2016).

According to Korve et al. (2001), the Light Rail Transit (LRT) alignments can be classified into 3 main categories, namely: a) exclusive, b) semi-exclusive and c) non-exclusive. A bigger percentage of fatal accidents appeared in exclusive and semi-exclusive alignment, while in non-exclusive, the absolute number of recorded accidents was much higher, as it is mentioned in the last study. According to Naweed and Rose (2015) and Naznin et al. (2017), tram driving is a complex task, which requires a high level of workload, since the driver should run on time, maintain his/her concentration and predict the behavior of other road users especially in non-exclusive alignments. Naznin et al. (2016) estimated that an increase of 1 unit in the tram's average speed, increases the probability of fatal crashes by 11.8%. Higher tram speeds were mainly observed in semi-exclusive sections.

This study deals with tram safety problems that occur in urban areas, where many interactions between trams and vulnerable road users (VRUs) appear. Urban streets, where the tramway is shared with pedestrians/cyclists, or semi-exclusive sections with many pedestrian/cycling crossings are of interest in this study. Different perspectives of tram safety are considered in the analysis in order to describe and explain well safety issues, that are observed in urban areas. The main goal of this analysis is to determine some practical measures, that aim to improve safety in tram networks without downgrading system efficiency. Furthermore, this study aspires to contribute to the scientific research of traffic safety by developing methodological tools, which can be utilized in order to understand better subjective notions of tram safety, such as perceived safety and driving stress, and to estimate the relationships between the previously mentioned variables and the design variables. Further details about the research objectives and questions of this study are presented in chapter 3 "Research Questions".

To do so, a flow diagram was developed in the early phases of the analysis (see figure 1.1). The first step of this study is to present findings from previous studies, that examined: design of tram lines, behavior and workload of drivers and tram safety in general. The stage of the literature review is crucial in order to determine research gap(s) and define better the research objective(s) and question(s). Methods and theories, that are used in the literature for the examination of tram safety problems, are taken into account in order to define the methodological approach in the next step. At this stage, two European networks were selected to be the study cases, namely those of Amsterdam and Athens. The selection process of the study networks was based on the design characteristics of each tram network and the willingness of tram operators to cooperate in this research. The results are related with three different perspectives of traffic safety, namely: perceived (or subjective) safety, driving stress and objective safety. In the Discussion chapter, the results are discussed and compared in order to determine the main findings of this thesis. The main findings and the ones from previous research studies are utilized for the extraction of scientific recommendations and practical recommendations. The practical recommendations refer to designs and ideas that can improve current safety conditions, while in the sub-chapter of scientific recommendations, a discussion, regarding the next research steps, is opened.

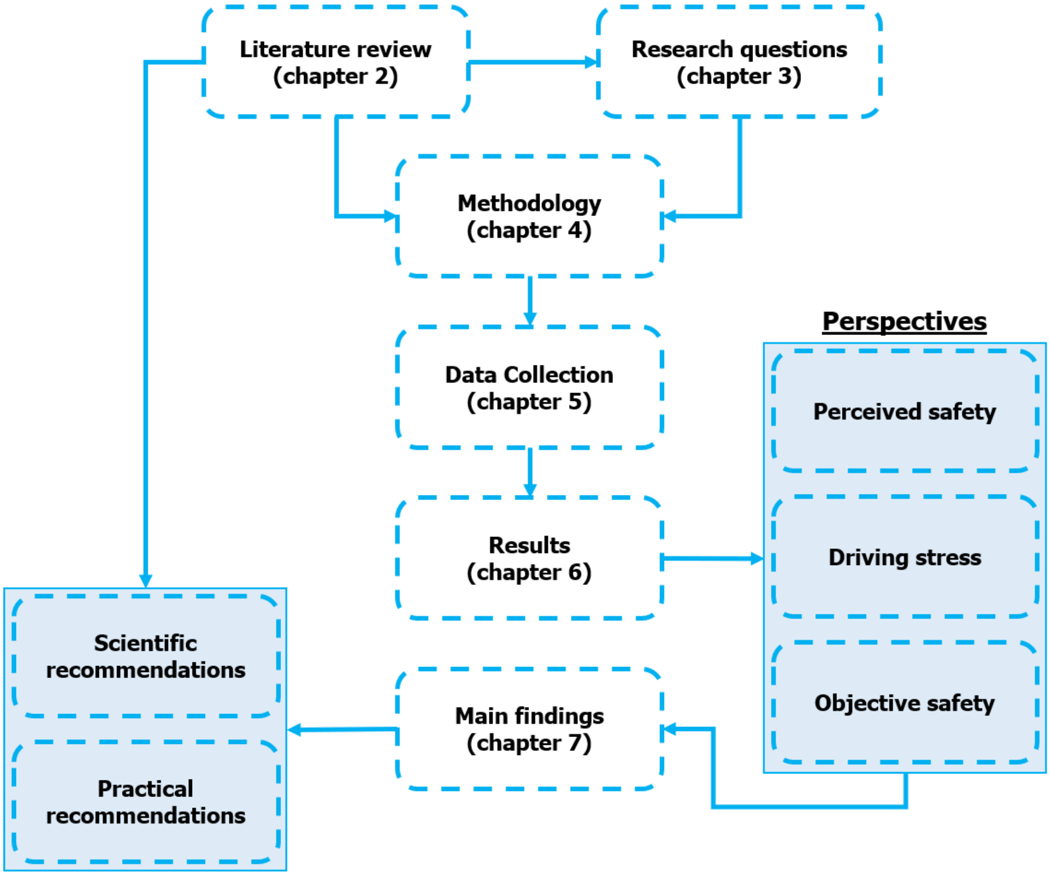

Figure 1.1: Thesis flow chart

It is expected that differences between perceived safety and driving stress will be identified especially in non-exclusive tramways. Perceived safety may increase as the level of separation of the tram track rises. In addition, in this thesis, it is assumed that the tram drivers lower tram speed, when they are driving in sections with presumably low safety. Therefore, the fluctuation of tram speed is expected to be similar to the fluctuation of perceived safety along a tram line. In practice, the differences in perceived safety levels can be used for the identification of design inconsistencies along tram lines. Another assumption is that driving stress is mainly influenced by perceived safety. Additional parameters of this subjective notion of tram safety may be: fatigue, load of standing passengers, delay and familiarity. Increased driving stress is expected to result in higher probability of a fatal accident. Also, this last probability increases when the tram speed exceeds 30 km/h. Therefore, more fatal accidents are expected to be observed in exclusive and semi-exclusive alignments (i.e. high level of separation of the tram track) than in non-exclusive alignments. The probability of a fatal crash is expected to be very low in sections, in which the tram track is fully shared with pedestrians; yet, the total number of accidents is likely to be higher in these sections compared to the ones with high level of separation.

All the previously mentioned expectations are based on the concept of shared space. This concept states that traffic safety can be improved by creating more subjective danger in the road environment (Methorst et al., 2007; Hamilton-Baillie, 2008; Moody and Melia, 2013). According to Methorst et al. (2007), this assumption is totally based on the "law of the jungle" and it is not substantiated by accident statistics. This thesis can give some extra clues regarding the validity of the shared space concept.

2
Literature review

In the last thirty years, many interesting studies have tried to examine tram safety by following different approaches, such as: assessment of tram lines design (Korve et al., 2001), description of tram drivers' behavior (Naweed and Rose, 2015; Naznin et al., 2017) and statistical analysis of past accidents data (Hedelin et al., 1996; Naznin et al., 2016; Marti et al., 2016; SWOV, 2011). The objective of the literature review chapter is to discuss the research theories and findings from all the different perspectives of tram safety, so that the research gap(s), objectives and questions will be feasible to be defined in the next chapter.

2.1. Infrastructure design

The design of a tramway begins with the selection of the tram alignment type that fits in the preexisting characteristics and functionality of each urban street. The main criterion for the determination of the tram design speed is that the speed of trams has to be almost similar to the speed of traffic (Office of Rail Regulation, 2006; CROW, 2013). Considering the design speed and the availability of urban space in each city, geometrical characteristics like the radius of the horizontal/vertical curves and superelevation are chosen by the designer afterwards (Yarra Trams, 2003). In addition, the designer has to determine the position and the type of the pedestrian/cycling crossings. By taking into account the future passenger-pedestrian traffic, he/she creates designs of tram stops (or tram stations). As it is presented in the next sections, due to the existence of many and important constraints in the urban centers, many different designs of tram alignments, crossings and tram stops have been developed and implemented in modern cities (Korve et al., 1996). Therefore, the development of a consistent design, that is capable to mitigate the risks, is a very interesting challenge for every rail engineer.

2.1.1. Tram lines design

Most of the times, tram tracks are installed on urban streets that have already been constructed. The available urban space is limited and the design of the tram line has to adjust to the characteristics and the functionality of each street. The existence of many important constraints in the selection of the optimal design for each road resulted in the development of many different types of tram alignments.

The first effort for the classification of the different designs of cross sections of tram lines was made in the TCRP Report 17 (Korve et al., 1996). The authors created three classes of designs, namely: the exclusive (type a), the semi-exclusive (type b) and the non-exclusive alignment (type c). In the first type, the tram line has a full-grade separation of both motor vehicle and pedestrian facilities (Cleghorn et al., 2009). In type b, the separation still exists, although in some spots of the line there are grade crossings, where the tram intersects with motor vehicles, bicycles and pedestrians. Mixed traffic operations occur in non-exclusive alignments. In some cases, the tram lane is shared with buses or other public transport modes and in some other cases, it has been aligned in pedestrianized zones, like city squares or shopping centers. In table 2.1, pictures per alignment type are presented. According to Korve et al. (2001), the share of fatal accidents in type b.1 and type b.2 alignments is 29%, while in the other types of semi-exclusive and non-exclusive alignments, this percentage is equal to 18%. A similar classification of light rail alignments was recommended by van der Bijl et al. (2018).

According to this study, the main types are: shared-space, traditional street-based (the tram line is fully integrated in regular traffic), traffic lane (tram line is separated from the other traffic lanes by painted lines), separate tramway, metro style tramway and railway for tram-train. Yet, in some cities, like in Melbourne (Australia), some small and at the same time significant differences in the set of categories may be observed. According to the study of Diemer et al. (2018), the alignments in the tram network of Melbourne can be classified into 5 categories based on the type of separation. The no-separation (M1) type is a non-exclusive type of alignment, where mixed traffic operations occur. In the part-time (M2) separation, the tram lane is separated from the motorized traffic only during peak hours and in the shared separation, the tram lane is shared with pedestrians. The tramway is differentiated from the traffic lanes of the street by painted lines in the M4 type, while the M5 type refers to right-of-way (ROW) alignments. As it can be seen in table 2.1, the general classification of Korve et al. (1996) and the specialized one of Diemer et al. (2018) can be matched appropriately.

The design speed is mainly connected with the type of tram infrastructure and with the context of the surrounding area. The number of VRUs in the road environment is also an important parameter, that is connected with the spatial characteristics of a district and influences the tram speed limits. Naznin et al. (2016) have proved the strong relationship between the speed and the number of fatal accidents (more details in sub-chapter 2.3). In urban areas, such as shopping centers, where the volume of pedestrians is relatively high, the tram velocities have to be surely lower than 30 km/h, while in the outskirts it can reach 50 km/h (Yarra Trams, 2003). According to the Dutch guidelines about the design of tram infrastructure (CROW, 2013), the speed limit for tram/pedestrian malls is equal to 18 km/h. The tram cannot run with a speed higher than 30 km/h in residential areas and city centers, where the tram lane is often shared with the motorized traffic. In the semi-exclusive and exclusive alignments in residential areas located in the suburbs, the tram can operate with velocities higher than 30 km/h and lower than 70 km/h. Furthermore, according to many guidelines, the rule of the thumb, i.e. that the speed of the tram has to be similar to the speed of the traffic in on-street tramways and a bit higher in off-street tramways, is followed (CROW, 2013; Office of Rail Regulation, 2006; Yarra Trams, 2003).

Other important parameters that affect the design speed of the tram is the radius and the superelevation of the curve. It is well-known to railway engineers that rail vehicles derail when their speed is higher than the overturning speed, so that the centrifugal force overcomes gravity (Parsons Brinckerhoff Inc. et al., 2016). According to Yarra Trams (2003), in curves with radius lower than 100 m, the tram should run at a speed lower than 15 km/h. The speed limit of 30 km/h is for turns with radius equal to 101-240 m and the limit of 45 km/h for turns with radius equal to 241-430 m. In Melbourne, the minimum radius is set to be equal to 25 m in the city streets and equal to 350 m in the outskirts. In tangent tracks, a superelevation of 6 mm is commonly used and in curves, the superelevation cannot exceed the 100 mm (Yarra Trams, 2003). Lastly, there are restrictions regarding the length of the tangent segment between two reverse curves. A minimum value of 10 m is selected (Yarra Trams, 2003), so that the passenger will have enough time to adjust to the changes of the direction (American Railway Engineering and Maintenance-of-Way Association, 2009).

The existence of slopes affects tram speed and traffic safety in general, since the tram vehicle has higher mass compared to the other urban transport modes. Therefore, it needs longer distance to reach the recommended maximum speed between two stations and to brake until standstill in the case of an unexpected event (SWOV, 2011). According to Yarra Trams (2003), the maximum grade of the tram line is equal to 6.67%. In addition, a value between 750 m and 2000 m is selected as a minimum radius for vertical curves.

2.1.2. Pedestrian/Cycling crossings

In urban spaces, pedestrians/cyclists are free to cross the tram tracks at any point. Nevertheless, the designer should define particular crossing points in each tram section of the network, as it is mentioned in the guidelines of Office of Rail Regulation (2006). The VRUs should be encouraged to use these points to cross the tramway. At crossing spots, clearly recognized features should be installed, such as: signing, pedestrian signals, dropped kerbs and planters.

In the TCRP Report 137 (Cleghorn et al., 2009), the most important designs of pedestrian/cycling crossings are presented in a list. The audible warning devices are very common in tram networks throughout the world. They are used in conjunction with flashing light signals at grade crossings (Cleghorn et al., 2009). The purpose of these systems is to attract the attention of VRUs and to notify them regarding the potential risks when they enter the tram area.

Classes 1 (Korve et al., 1996)	**Types 1**	**Description 1**	**Classes 2** (Diemer et al., 2018)	**Design Speed**	**Examples**
Exclusive	**Type a**	Fully grade separated or at grade without crossings	**Physical separation (M5)**	≤ 70 km/h	
Semi-Exclusive	**Type b.1**	Separate right-of-way		30-50 km/h	
	Type b.2	Shared right-of-way protected by barrier curbs or fences		30-50 km/h	
	Type b.3	Shared right-of-way protected by barrier curbs		30-50 km/h	
	Type b.2	Shared right-of-way protected by mountable curbs, striping and lane designation	**Visible separation (M4)**	30-50 km/h	
	Type b.5	Tram/pedestrian mall adjacent to a parallel roadway	**Shared separation (M3)**	≤ 20 km/h	
Non-Exclusive	**Type c.1**	Mixed traffic operation	**No separation (M1)-Part time separation (M2)**	20-30 km/h	
	Type c.2	Transit-only mall	**Shared separation (M3)**	20-50 km/h	
	Type c.3	Tram/pedestrian mall		≤ 20 km/h	

Table 2.1: Tram alignment types
Source: Korve et al. (1996); Diemer et al. (2018); Own Elaboration (2019)

Figure 2.1: Pedestrian/cycling crossing with flashing lights in Delft, the Netherlands
Source: Google Earth StreetView

The pedestrian automatic gate is a system, that can be additionally installed in order to further strengthen traffic safety (Cleghorn et al., 2009). When the tram passes from the area, the streams of VRUs are blocked by the gates. The function of this system is the same as the function of the classic gates, that are installed in rail crossings on roadways. The pedestrian swing gates (sometimes called pedestrian fence gates) is a completely manual system. The VRU is completely free to open the gate to enter the crossing area. The main purpose of this design is to discourage pedestrians from making dangerous crossing movements (Cleghorn et al., 2009). In addition, the existence of fence gates forces the VRUs to check the tramway more carefully before crossing it.

The offset pedestrian crossing, or Z-pedestrian crossing, is a new modern design. By installing some barriers or fences, the pedestrian movements are channelized. The purpose of this type of crossings is to increase pedestrian awareness of an oncoming tram. This design has been used mainly near the stations, where a big number of pedestrians cross the track when a tram arrives (Cleghorn et al., 2009). In addition, refuge islands, that separate the tramway from the roadway, can reinforce traffic safety. With this design, the pedestrian can cross the tramway in the first phase, if there is no tram approaching the spot. In the second phase, the refuge islands provide enough space for him/her to stay waiting for the green light (protected crossing) or to check carefully the roadway before crossing it (unprotected crossing).

Figure 2.2: Pedestrian crossing with swing gates in San Jose, USA
Source: Cleghorn et al. (2009)

All the previously mentioned designs are observed mainly in exclusive or semi-exclusive tram alignments. In the non-exclusive designs, either there is no crossing (e.g. pedestrianized zones) or there are conventional zebra crossings with or without traffic lights (e.g. mixed operation streets). Lastly, it should be noted that the installation of unprotected crossings is not characterized as the best practice near schools. The Office of Rail Regulation (2006) recommends the installation of signals and advance warning systems, so that the tram driver will be ready to brake, when he/she enters a school area.

2.1.3. Tram stop design

According to the Office of Rail Regulation (2006), the needs of passengers/pedestrians should be reflected in the design of tram stops and associated pedestrian routes. The platform width is a very significant parameter of traffic safety. The designer must provide enough space for passenger boarding and alighting. He/she has to consider the movements of pedestrians in the urban space, since the tram station should be considered part of the walking infrastructure (Office of Rail Regulation, 2006). On the contrary, spaces in the dense and crowded city centers with high traffic volumes are very limited. Designers have tried to solve this problem by developing many different designs of tram stops. The tram network of Melbourne is famous for the many different designs of tram stops (see figure 2.3); some of them have already been characterized as unsafe (Currie and Smith, 2006; Currie and Reynolds, 2010; Currie et al., 2011).

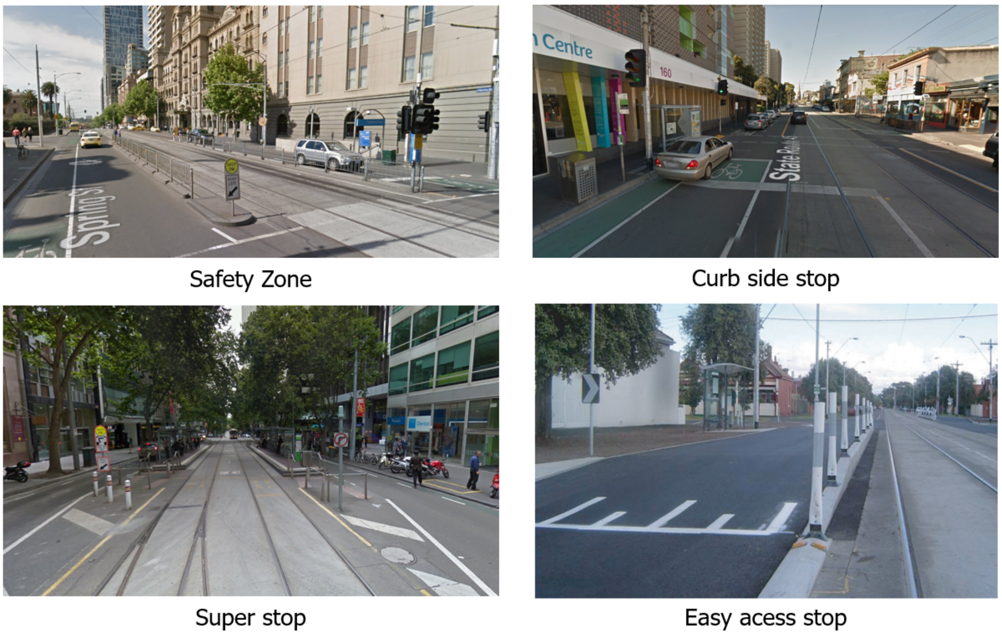

Figure 2.3: Tram stop designs in Melbourne, Australia
Source: Currie and Smith, (2006); Currie and Reynolds, (2010); Google Earth StreetView; Own Elaboration (2019)

The four different types of tram stops observed in the network of Melbourne have been discussed by Public Transport Research Group of Monash University (Currie and Smith, 2006). The first and most unsafe design is the safety zones. In this type of tram stop, passengers wait on a small narrow strip located in the middle of the street and near the tram track (Currie and Reynolds, 2010). Some metal barriers protect the pedestrians from the motorized traffic. Signalized pedestrian crossings provide access to these areas. In the curbside stops, the platform is constructed on the edge of the extended curb (Currie et al., 2011). In the period between 1999 and 2009, approximately 38-53 accidents per year were reported in curb-side stops in Melbourne (Currie et al., 2011). The Super Stops are located in the center of urban roads. At these points, the two-lanes per direction roads are narrowed to single lane per direction road. The passengers have access to the tram platforms by two protected crossings. In modern tram networks, such as Athens and Rotterdam, the Super Stop is the only tram stop design that appears in central areas. The last design, that is observed in Melbourne, is the easy access stop; the tram track is still located in the middle of the street, but the passengers wait on the curb. Between the tram track and the sidewalk, there is a raised road surface, that is used as a platform. Due to the existence of a raised road surface, the car drivers are forced to drive at lower speed (Currie et al., 2011). The replacement of the older tram stop design (i.e. safety zone and curbside stops) with new designs (i.e. super stops and easy access stops) resulted in a reduction of auto-pedestrian collisions by 62% and auto-tram collisions by 12% (Currie and Reynolds, 2010). Unfortunately, the last research showed that the tram-pedestrian accidents slightly increased. Figure 2.3 illustrates the four different designs observed in the tram network of Melbourne.

2.1.4. Design consistency

According to Messer (1980), the design inconsistency can be described by a geometric feature or the combination of the adjacent features, that have such unexpectedly high driver workload that motorists may be surprised and possibly drive in an unsafe manner. There are multiple ways to measure design inconsistency. Most of the studies focus on four main areas: operating speed, vehicle stability, alignment indices and driver workload (Ng and Sayed, 2004; Torregrosa et al., 2013).

When it comes to operating speeds, many different indicators have been utilized in past studies. The most popular indicators are based on the 85th percentile speed ($V85$) of a sample of vehicles, as Torregrosa et al. (2013) mentioned. In an inconsistent segment, the average value ($\Delta V85$) and the standard deviation ($\sigma\Delta V85$) of speed differences have been reported to be higher in comparison with a consistent road segment. Another indicator that is used in the research is the difference between the average operating speed ($V85$) and the speed limit (L). Design consistency can also be described by the average values of distances used for deceleration in one road segment ($L\Delta V85$) (Torregrosa et al., 2013).

The previously mentioned indicators describe the observed outputs of the driving task. In other words, they give details about the behavior of the driver; yet, it is not possible to interpret the causes behind the observed driving behaviors. This is why the driver workload seems as a more appealing approach for identifying design inconsistencies, as Ng and Sayed (2004) have stated. According to Messer (1980), driver workload can be defined as the time rate at which drivers must perform the driving task that changes continuously, until it is completed (more details about workload in sub-chapter 2.2.2). However, Torregrosa et al. (2013) argues that indicators related with workload are more subjective and much more complex; thus, they are less used. Hassan (2004) asked 21 experts to evaluate the workload of 9 basic geometric features by utilizing a subjective rating scale - from 0 (no problem) to 6 (severe problem). Furthermore, De Waard (1996) recommended heart rate measurements in order to monitor the changes in workload during performance.

In the literature, there are no studies that have attempted to examine tram safety by taking into account design inconsistencies of tram lines. Nevertheless, the concept of design consistency is quite relevant with tram line design, since the tram driver partly drives in situations with separate lanes that are signal-controlled and partly in situations mixing with road traffic and pedestrians, according to SWOV (2011). Indeed, table 2.1 presents all the different designs of tram alignments. As it has been mentioned in the section 2.1, speed limits are directly connected with the type of the cross section. Furthermore, the behavior and workload of tram drivers are also linked with the number and the type of pedestrian/cycling crossings that exist in each section. There are many different types of crossings and many different designs of stations, as it has been pointed out above, and all of them can be seen along a single line. This fact results in high speed and workload variations. SWOV (2011) recommended that advanced training is required, so that the tram driver will respond properly to design inconsistencies.

2.2. Human Factors

The number of studies (Naweed and Rose, 2015; Naznin et al., Naznin et al.) that attempted to discuss the behavior of tram drivers in the mixed traffic reality of urban areas is very limited, compared to the studies (Michon, 1985; Fuller, 2005) about the behavior of car drivers. In this section, theories and findings from studies about car driver behavior and workload are combined with the few research findings related with the interactions between trams and pedestrians. The main goal is to understand better the challenges that a tram driver faces every day.

2.2.1. Driver behavior theories

In the past, many studies have attempted to understand the behavior of (mainly car) drivers. Michon (1985) proposed that the driving task is divided in 3 main levels: the strategic level, which is related with the route choice, the tactical level, which is related with the speed choice or the lane choice, and the operational/control level, which is related with the acceleration or the steering process. In tram driving, the driver cannot select the route and control the lateral movements of the vehicle. The human operator controls only the speed of the tram by respecting the speed limits and considering the movements of pedestrians, cyclists and vehicles.

Rasmussen (1987) developed a taxonomy based on levels of skill of conscious control of the vehicle. The knowledge-based tasks refer to how familiar the tram driver is with the tram routes. The rule-based skills are related with the set of rules established for driving sub-tasks, so that they will be performed well by the driver. As it has been mentioned, every section of the tram line has its own speed limits that should be respected by the drivers without too much thinking. He/she must check the traffic signs and lights, that are dedicated to tram operations; in addition, he/she has to be aware of the traffic rules of the rest traffic (e.g. cars, pedestrians, cyclists, etc.), while he/she is driving in a segment located in an urban area. The skill-based level is related with the competence of the driver to respond automatically and without errors in any interaction or any unsafe event. It surely demands a lot of experience to reach this level. Experience is necessary especially for tram drivers, since they have to adjust their driving behavior and consequently the speed of the rail vehicle accordingly, by considering and predicting the movements of the other road users (Naznin et al., 2017). Tram drivers must be able to brake immediately in the case of a sudden event that nay occur every day in tram operations.

In the study of Fuller (2005), more attention is paid to the fact that people tend to adapt their behavior to the new driving circumstances, when the driving situation changes. One relevant example is the case when the flow of pedestrians in a pedestrianized zone increases to very high volumes; consequently, the task demands increase and the tram driver starts feeling unsafe, if his/her driving capabilities are not adequate for these traffic conditions. The driver loses control of the vehicle when the task demands are higher than his/her capabilities. Tram drivers face complex interactions every day and it needs good professional experience, training and a high level of competence, so that they will be able to react properly in any unsafe event.

2.2.2. Workload theories

Pauzie (2008) has mentioned that the individual can adjust his/her behavior in the case of an increase in task demands by selecting between two options: more effort with no perceptible effect on performance or no additional effort leading to lower level of performance. Therefore, workload is related with the complexity of the task and the amount of resources that the operator is willing or able to allocate (Pauzie, 2008).

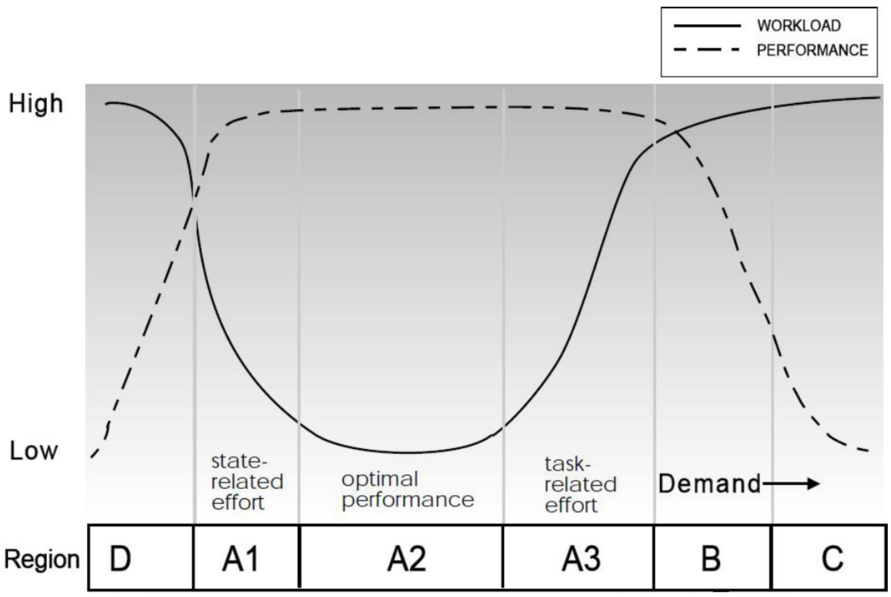

Figure 2.4: Workload vs driving performance
Source: De Waard (1996)

According to the Driver Activity Load Index developed by Pauzie (2008), workload has 6 main factors, namely: effort of attention, visual demand, auditory demand, temporal demand, interference and situational stress. The first factor is related with the attention required for the activity. To perform a task well, the driver has to mind the road environment and listen to the sounds of other road users. A small-time interval to run an activity demands that the driver think and decide very quickly. Quick thinking requires much more effort and increases driving stress. Disturbances, like radio, phoning, etc., increase the workload. Moreover, the driving workload is related with psychological factors like insecure feeling (or perceived safety), irritation and discouragement.

De Waard (1996) tried to describe the relationship of workload and driving performance. He developed a graph (figure 2.4), which points out that workload and performance have an inverse relationship. In the D-region, the state of the driver is affected by an increase of the task demands. One relevant example is when a tram enters from a semi-exclusive section into a shared space section. In the first stage, the workload is getting higher and the performance is not satisfactory. When the driver is ready to deal with the new driving situation, his/her performance starts improving, while the workload is decreasing (region A2). It should be noted that sometimes the new driving situation is so complex that the driver is unable to adapt his behavior to it. Then, the human operator is overloaded i.e. region C and D; in those regions, he/she is no longer able to perform the driving task well.

Theeuwes et al. (2012) discussed the effects of high driving workload. From a physiological perspective, the additional effort for high driving performance is connected a high heart rate (HR), with high skin response and pupil change. Moreover, overload causes tunnel vision, a driver to be more error prone and information is selectively collected from the road environment. Yet, it should be noted that workload is more a subjective (relative) rather than an objective concept. In the last decade, some researchers have attempted to approach the objective nature of this notion by developing and applying measurements of heart rate and skin response (Mehler et al., 2009; van Gent et al., 2018). They collected physiological data by utilizing medical devices like: Holter heart monitor and Photoplethysmography (PPG) sensors. Mehler et al. (2009) proved that heart rate data is sensitive to changes of driving workload. Another approach, that considers both the objective and the subjective nature of this notion, is the creation of a questionnaire survey to measure driving stress. Hill and Boyle (2007) developed 18 driving scenarios and they asked the respondents to assess the level of stress on a 7-point Likert scale from 1 (very stressful) to 7 (not stressful at all). They ended up with some beta parameters that indicate the relationship of stress with some special driving conditions, such as: night driving, driving behind a vehicle that is moving slower than the speed limit, merging into heavy traffic, etc.

In the literature, there is no research that has ever tried to examine the workload of a professional tram driver. Due to the existence of many design switches and spots with high traffic volumes in a single line, it is expected that the variations of workload of tram drivers will be quite high compared to other drivers.

2.2.3. Challenges of tram drivers

Two past studies from Australia attempted to explain the behavior of tram drivers in a mixed traffic road environment and pointed out some of the key challenges. Both studies presented qualitative information, since they are based on interviews with the tram drivers of the network of Melbourne. Naweed and Rose (2015) has mentioned that tram driving is a very complex task that demands experience and advanced training. The main problem is that task demands are similar to those of train drivers and motor vehicle drivers combined. In a mixed traffic reality, the tram driver needs to keep everyone safe controlling only the longitudinal movements of the vehicle and not the lateral ones, as the car driver can (Naznin et al., 2017).

In the interviews, one of the tram drivers pointed out that every day at work, he has to pay extreme attention, since everyone in the road (i.e. pedestrians, cyclists, cars, and motorcycles) interfere with the tram path (Naznin et al., 2017). Indeed, especially in the city centers the traffic is so dense that a tram driver is not able to take his/her eyes from the street. According to a second driver with 7 years of experience, this daily reality exhausts the tram drivers mentally (Naznin et al., 2017). A third driver remarked that some of his/her colleagues had accidents while they were assisting passengers (Naznin et al., 2017).

One of the main daily challenges of tram drivers is the necessity to predict the behavior and the movements of the other traffic actors in order to increase/decrease the vehicle speed and avoid dangerous situations (Naweed and Rose, 2015; Naznin et al., 2017). Furthermore, on-time running is a second and very important challenge. Most of the times, tram drivers are evaluated on their on-time running performance by the company managers (Naweed and Rose, 2015; Naznin et al., 2017). The pressure for the minimization of delays influences negatively the performance of the driver and consequently, safety (Naweed and Rose, 2015). Emergency braking is an option provided by the system in order to avoid a collision. Yet, it can result in falls of standing passengers inside the cabin (Naznin et al., 2017); therefore, many drivers tend to avoid this option. In general, a tram driver should take care of people's safety inside and outside of the tram. Lastly, experience is very significant when it comes to dealing with high driving workload that can lead to fatigue and downgraded driving performance (Naznin et al., 2017). Figure 2.5 illustrates all the previously discussed key challenges.

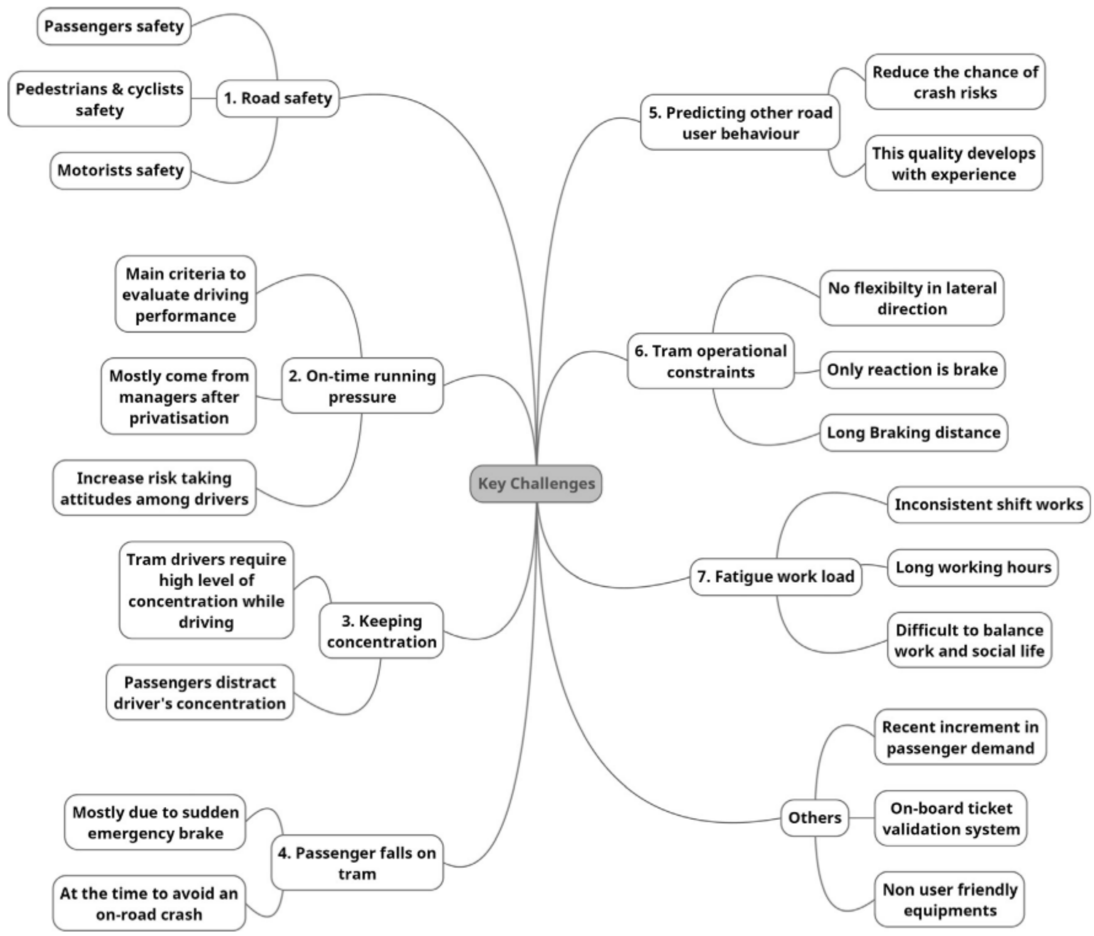

Figure 2.5: Key challenges of tram driving
Source: Naznin et al. (2017)

2.2.4. Vulnerable road users behavior

The study of Naznin et al. (2017) also dealt with the behavior of vulnerable road users (VRUs). The main problem identified by the tram drivers is the lack of awareness among pedestrians and passengers, when they are interacting with a tram. In stations, passengers cross traffic lanes and tram lanes without checking in order to get on the tram. When the tram arrives, the passengers who get off start walking in front of the tram vehicles, without thinking that the tram may get moving. Another rule violation is when an individual who wants to board the tram attempts to overtake the rail vehicle, so that they will not miss it in the next stop. Naznin et al. (2017) mentioned that a critical problem is that some pedestrians do not fully understand the rules related with tram operations. The problem is getting worse with some tourists who are not familiar with mixed traffic reality.

Castanier et al. (2012) conducted a questionnaire survey to identify the perceptions of pedestrians, cyclists and motorists regarding the probability of a crash with a tram. In the first phase (excluding demographic questions), the respondents were asked to rate the likelihood of experiencing a crash with a tram and the likelihood of an average person experiencing the same event. The next section was related with the behavioral intention to cross tram tracks in front of an oncoming tram. Lastly, respondents evaluated the frequency of incidents involving a tram, as observed by them. The main outcome of the study of Castanier et al. (2012) was a globally low perceived crash risk, in all age groups. This result confirms the previously mentioned views of the tram drivers of Melbourne (i.e. lack of situational awareness among pedestrians). Furthermore, the respondents thought that the probability to be involved in an accident with a tram is lower for themselves and higher for the others (comparative optimism). In this study, young pedestrians seem to have the most accurate awareness of tram risks compared to all the other age groups. Lastly, pedestrians with high comparative optimism reported less intention to cross a tram track in front of an oncoming tram than pedestrians with no comparative optimism (Castanier et al., 2012).

2.3. Tram safety

One of the first studies that engaged with tram safety was the study of Hedelin et al. (1996) in several Swedish cities. The main finding was that 69% of fatal accidents and 24% of non-fatal ones occurred near or at stops. The annual average rate of non-fatal and fatal events was 39 and 3, respectively. In tram collisions, the estimated risk of death for pedestrians is about 100 times higher compared to the collisions with motor vehicles.

In the Netherlands, when SWOV (2011) compared the casualties rates, they found that the rate of severe tram crashes with VRUs is 12 times bigger in comparison with the same rate of car crashes. In the decade 2000-2009, the annual number of casualties among public transport users was 1 fatality and 19 serious road injuries. Yet, the number of collisions between trams/trains and other road users was much bigger, i.e. 38 accidents with severe injuries and 25 fatal accidents per year. Therefore, it is safer to be inside the tram as a passenger rather than walking or cycling outside and next to it.

Variables		Fatal	Non-Fatal	Chi-square (p-value)
Driver age	Between 20–30 years	5 (13.2%)	33 (86.8%)	
	Between 30–40 years	36 (7.2%)	463 (92.8%)	
	Between 40–50 years	99 (8.4%)	1075 (91.6%)	
	Between 50–60 years	113 (7.1%)	1474 (92.9%)	
	Between 60–70 years	70 (8.2%)	784 (91.8%)	3.90 (0.563)
	More than 70 years	13 (9.0%)	131 (91.0%)	
Driver experience	Less than 3 years	26 (7.7%)	312 (92.3%)	
	Between 3–15 years	182 (7.6%)	2226 (92.4%)	
	Between 15–30 years	102 (8.8%)	1054 (91.2%)	
	Between 30–40 years	22 (6.1%)	336 (93.9%)	3.78 (0.436)
	More than 40 years	4 (11.1%)	32 (88.9%)	
Tram floor	Low floor = 1	89 (11.4%)	689 (88.6%)	17.25 (0.000)
	Otherwise = 0	247 (7.0%)	3271 (93%)	
Tram length	More than 16.64 m = 1	188 (8.3%)	2073 (91.7%)	1.61 (0.204)
	Otherwise = 0	148 (7.3%)	1887 (92.7%)	
Tram age	More than 14 years = 1	247 (7.0%)	3171 (93.0%)	17.25 (0.000)
	Otherwise = 0	89 (11.4%)	689 (88.6%)	
Season	Winter and Autumn = 1	158 (7.2%)	2045 (92.8%)	2.643 (0.010)
	Summer and Spring = 0	178 (8.5%)	1915 (91.5%)	
Light	Daylight = 1	255 (7.5%)	3142 (92.5%)	2.23 (0.135)
	Otherwise = 0	81 (9.0%)	818 (91.0%)	
Day	Weekdays = 1	271 (7.7%)	3263 (92.3%)	0.646 (0.422)
	Weekends = 0	65 (8.5%)	697 (91.5%)	
Traffic volume	Moderate/heavy = 1	100 (6.2%)	1508 (93.8%)	9.152 (0.002)
	Light = 0	236 (8.8%)	2452 (91.2%)	
Land use	Residential = 1	74 (6.9%)	997 (93.1%)	1.645 (0.200)
	Others = 0	262 (8.1%)	2963 (91.9%)	
Lane priority	Presence of tram priority = 1	196 (9.1%)	1969 (90.9%)	9.19 (0.002)
	Otherwise = 0	140 (6.6%)	1991 (93.4%)	
Average speed	Less than 16 km/hr = 1	131 (7.5%)	1608(92.5%)	0.337 (0.562)
	Otherwise = 0	205 (8.0%)	2352 (92.0%)	

Table 2.2: Risk factors and descriptive statistics of fatal tram accidents
Source: Naznin et al. (2016)

According to the research carried out by Marti et al. (2016), pedestrians and cyclists are much more likely than other second parties to be injured or die from a crash with a tram. Indeed, in Switzerland, the shares of tram accidents leading to severe injuries or deaths per second party group were 89.6% for pedestrians, 83.1% for cyclists, 60.0% for motorbike users, 24.9% for car occupants and 4.0% for truck occupants. Tram drivers were responsible only for 1 out of 13 tram collisions. Distracted pedestrians was one of the main causes of the tram-pedestrian collisions, that occurred in areas, where the tram infrastructure is shared with pedestrians. However, the accidents were more severe in right-of-way (ROW) or semi-exclusive alignments if a second party attempted to cross the tramway illegally.

In Croatia, according to Brčić et al. (2013), the 73% of tram crashes occurred in streets where the tramway is separated from the rest of the traffic. Nevertheless, they found that the probability of an accident between a tram and a second party is 11.5 times bigger in non-separated tram tracks compared to the one in separated tracks. They conclude that exclusive and semi-exclusive tram alignments improve tram safety and that traffic signalization is necessary in pedestrian crossings.

Variables	Coefficient	S.E.	Odds ratio	95% C.I. for Odds ratio	
				Lower	Upper
Tram floor (low floor = 1)	1.001[a]	0.23	2.722	1.741	4.255
Tram age (years)	0.026[a]	0.01	1.027	1.006	1.048
Season (Winter and Autumn = 1)	−0.201[a]	0.11	0. 818	0.653	0.983
Traffic volume (high/moderate = 1)	−0.373[a]	0.12	0.687	0.539	0.877
Lane priority (yes = 1)	0.343[a]	0.12	1.410	1.124	1.768
Speed (km/h)	0.112[a]	0.05	1.118	1.013	1.235
Constant	−5.132[a]	1.02	0.006		
Number of observations		4296			
Restricted log-likelihood (constant only)		1178.7			
Log-likelihood at convergence		1156.7			
Chi-square (p-value)		43.99 (<0.0000)			

[a] 95% significant level; S.E.: standard error; C.I.: confidence interval.

Table 2.3: Binary logistic regression model about fatal tram accidents
Source: Naznin et al. (2016)

Naznin et al. (2016) assessed the influence of 12 risk factors in tram safety. These factors were divided into four categories, namely: 1) tram drivers characteristics: age and experience, 2) vehicle characteristics: floor type, length of tram and age of tram, 3) environmental factors: lighting conditions, day of week and season of year, 4) road characteristics: traffic conditions, land uses, lane type and average tram travel speed. Table 2.2 shows the statistical results and table 2.3 presents the binary logistic regression model estimated in this study. One of the main findings is that one unit increase of average speed results in higher probability of a fatal accident by 11.8%. In congested traffic situations, the likelihood of fatal crashes is also lower by a factor 0.69. Furthermore, in sections with tram lane priority it is 1.41 times more likely for severe collisions to occur, than in sections without priority (Naznin et al., 2016) , such as tram/pedestrian malls. Other significant parameters are: the tram floor, the tram age and the season.

2.4. Conclusions

As it was seen in the previous sub-chapters, a plethora of studies (Korve et al., 1996; 2001; Cleghorn et al., 2009; Currie and Reynolds, 2010; van der Bijl et al., 2018; Diemer et al., 2018) has dealt with the design of tram infrastructure; they have presented many different alignment types, designs of crossings and stations. The different designs were classified as exclusive, semi-exclusive and non-exclusive, according to the level of separation. Some non-exclusive alignment types, like the tram/pedestrian malls and mixed traffic operations, increase the complexity of interactions between VRUs and trams. It was also stated that in most cases, design speed is mainly connected with the alignment type. Due to the existence of various designs, many design inconsistencies are expected to be observed along the tram lines. Definitely, design consistency is a very relevant concept and either speed profiles or workload deviations can be utilized as main indicators, as Torregrosa et al. (2013) and Ng and Sayed (2004) have shown.

By considering the theory of Fuller (2005), tram driving is a very demanding process, since the tram driver has to adjust his/her driving behavior (therefore the tram speed) according to the variable characteristics of different road environments. Proper training and competence are required, so that the tram driver is capable of performing as well as expected, especially in sections with many and complex interactions with VRUs, where the workload increases dramatically. According to the studies of Naznin et al. (2017) and Naweed and Rose (2015), tram drivers have to predict the movements of pedestrians/cyclists. Based on their predictions, they should increase or reduce the tram speed. Simultaneously, they should run on time (as their managers demand) and serve passengers accordingly. The pressure to the tram drivers is also increased by the lack of situational awareness, which was observed in many age groups of pedestrians in the study of Castanier et al. (2012).

It is a fortunate fact that, in the end, the number of tram accidents is relatively low compared to car accidents, as SWOV (2011) and Marti et al. (2016) have mentioned. However, in Switzerland, the percentage of tram collisions leading to severe injuries or deaths were 89.6% for pedestrians and 83.1% for cyclists. According to Korve et al. (2001), the share of fatal accidents is lower in non-exclusive than in semi-exclusive or exclusive alignments. On the contrary, Brčić et al. (2013) found that the probability of an accident between a tram and a second party is 11.5 times bigger in non-separated tracks compared to separated ones. Naznin et al. (2016) showed that an increase of 1 unit in average speed increases the probability of a fatal accident by 11.8%. As a result, the probability of a fatal collision is higher in the tram sections with lane priority (i.e. exclusive or semi-exclusive alignments).

3

Research questions

In the literature, few studies have examined more subjective concepts of tram safety, such as: perceived safety and the stress of tram drivers. Naweed and Rose (2015) and Naznin et al. (2017) were the first studies that dealt with the behavior of tram drivers and spoke about their daily challenges. The quantification of perceived safety or driving stress is necessary especially in the field of tram safety, since the tram accidents are very rare. As a result, it is really difficult to extract statistical significant correlations that can explain observed tram safety problems. Due to the limited number of accidents, there is no study that has ever tried to connect severe crashes with specific tram lines designs (see table 5.2) through the estimation of correlations or at least statistical trends. Lastly, as it was seen in the literature review chapter, pedestrians and cyclists are much more likely than other second parties to be seriously injured or die from a crash with a tram (Marti et al., 2016). In many tram networks of the world, there are sections located inside the city centers, where the tram infrastructure is completely shared with vulnerable road users (VRUs). A specialized research on the tram-VRU interactions, which occur in these shared space sections, has not been conducted yet.

The main research objective of this thesis is to examine tram safety in urban spaces, where the trams interact with VRUs. To export conclusions regarding the level of safety in these areas, multiple perspectives are considered in the analysis, namely: perceived safety, driving stress and objective safety. The quantification of subjective notions related with tram drivers' behavior and psychology, such as perceived safety and driving stress, is an additional objective of this thesis. Surely, the quantitative results should be estimated in such a way that can be compared with the results of objective safety in the next stages. The spatial patterns of recorded accidents ought to be analysed further and connections between locations with high concentration of severe tram crashes and designs of tram lines should be sought. By taking into account the statistical outcomes from these different perspectives, the last goal is related with the development of a list of practical measures, which can improve traffic safety without downgrading system efficiency. To meet all the previously mentioned objectives, a set of research questions that follows has been formulated.

Perceived safety is influenced by multiple factors; some potential factors are: alignment type, existence of a tram stop or pedestrian crossing or curve, visibility and traffic conditions. It is assumed that in sections with low perceived safety, tram drivers lower the speed of the tram in order to feel safer. In addition, driving stress is increased due to the feeling of insecurity. Yet, driving stress is not only affected by perceived safety; additional factors connected with tram operations, like on-time running, fatigue and the number of standing passengers, have an impact on it, as previous studies have mentioned (Naweed and Rose, 2015; Naznin et al., 2017). Therefore, the factors that are significantly correlated (in statistical terms) with perceived safety and driving stress in urban areas, where the tram interacts with VRUs, have to be searched in the first place.

- *Which factors have a significant impact on perceived safety and driving stress of tram drivers?*

On the other hand, tram safety can be examined in a more objective way by looking at accident records. It is questionable whether records of tram-VRU accidents from a single tram network are enough to analyse tram safety in sections, where the trams interact with pedestrians. Multiple times it has been mentioned that tram accidents are very rare and severe at the same time (SWOV, 2011;

Marti et al., 2016); therefore, it can end up being difficult to find designs or traffic conditions that are objectively unsafe, only by looking at these records. Therefore, the first research question related with objective safety perspective examines whether tram accidents records can be proved useful in this analysis. An alternative approach is to find the locations in tram networks, where many emergency brakings are recorded in the speed profiles. A high number of emergency brakings can confirm the existence of many traffic conflicts in a particular urban area. Both recorded accidents and traffic conflicts can be used to examine objective safety; this is why the term "severe unsafe events" is used in the second research question. The availability and the data quality will be the main factors in order to select which type of objective safety data will be used in the next stages of this analysis.

- *Can we learn something from past accidents between trams and VRUs?*
- *Is there any connection between the alignment type and the frequency of severe unsafe events with VRUs?*

Perceived safety and driving stress are important factors, that are able to explain marked modifications in tram driving behavior. Past accidents offer some evidence regarding objective safety. Objective safety is not necessarily "in line" with perceived safety. Tram drivers may pay less attention while driving in sections with high perceived safety. Furthermore, the average tram speed is expected to be lower in alignments with low perceived safety; lower tram speed results in lower probability of a fatal accident, as Naznin et al. (2017) have estimated. Hence, by answering the fourth research question, the author will be able to conclude if tram drivers in general perceive safety appropriately. Tram alignments with high differences between perceived and objective safety will be searched in this analysis. Surely, the reasons for the appearance of these differences should be discussed. On the other hand, if the differences between these two perspectives are not great, then safety, as it is felt by the tram drivers, can be used as an indicator in order to develop safer designs of tram lines.

- *What are the differences between perceived and objective safety and in which road design environments do they differ?*

If we assume that tram drivers reduce tram speed in sections with low perceived safety level, then perceived safety deviations instead of speed deviations can be used as an indicator to identify design inconsistencies along tram lines. As it has been mentioned, the statistical correlations between perceived safety and design can be estimated through the development of a statistical model; therefore, the future designer will be able to predict the new perceived safety level if he/she decides to alter the design of the tram line. Definitely, connecting theory with practice will not be an easy process. Many difficulties are bound to appear in this process. In the last research question, the author of this thesis will attempt to see if there are ways for these difficulties to be overcome. One parameter that limits the potential options in the development of a completely safe design is system efficiency. Travel time is a significant factor that is directly linked with the speed of the rail vehicle and impacts the attractiveness of the tram as a mode of transport. Tram companies wish to increase the reliability of tram operations in order to increase the ridership. Yet, it is really questionable how tram operation can be efficient and reliable, especially in urban road environments, where many and complex interactions between tram and VRUs occur. Balancing safety with system efficiency is surely a great challenge for every transport engineer.

- *Can the findings from models be utilized in order to develop a list of interventions that could reinforce tram safety without downgrading system efficiency?*

4

Methodologies

The objective of this chapter is to describe the methodologies (i.e. the theoretical frameworks), according to which the research questions can be answered. In this study, three main methods are used, namely: stated preference experiments, ordinal regression and black spot analysis. The stated preferences experiment is conducted in this thesis for the examination of subjective notions of tram safety, namely: perceived safety and driving stress. Ordinal regressions are executed to estimate models for each of the previously mentioned notions. By estimating the beta parameters of the models, the relation between explanatory variables, such as: alignment type, volume of VRUs, arrival delay and load of standing passenger, and perceived safety or driving stress can be estimated. The other perspective of tram safety, which should be examined in this study, is the objective safety. Black spot analysis using tram accidents is able to point out some interesting spatial patterns. The relationship between the concentration of tram-VRU accidents and explanatory factors, like tram line design and traffic conditions, can be discussed in the next steps of this study.

4.1. Stated preference experiments

The stated preferences experiments were originally developed in marketing in the early 1970s (Kroes and Sheldon, 1988) and have been routinely applied in transport research since then (Hensher, 1994). According to Kroes and Sheldon (1988), stated preferences methods refer to a family of techniques, that utilizes the preferences of survey respondents regarding a set of transport options to estimate utility functions. The researcher is responsible for constructing a set of different transport situations or contexts in the beginning of this process. The description of these scenarios is achieved by selecting the right words (for categorical explanatory variables) and values (for continuous explanatory variables). Of course, some of these developed scenarios may not exist in reality.

The last fact is at the same time the main advantage and disadvantage of stated preferences experiments. The answers of the survey participants can be biased as the choices (or preferences) are made by taking into account imaginary transport situations. People may not necessarily do what they say, as Kroes and Sheldon (1988) mentioned. On the contrary, in revealed preferences experiments, the data is more valid, because the choices of people are observed in reality (real observations). Yet, there are strong correlations among independent variables (or explanatory variables); in the end, these correlations make it difficult to estimate statistical models with significant parameters (Kroes and Sheldon, 1988). Subjective notions, like perceived safety, cannot be measured in reality; stated preferences experiments can be applied for the quantification of these notions. Another advantage of stated preferences experiments, many different independent variables can be selected in the beginning of the process, while in revealed preference experiments, the set of independent variables is standard in the first place.

Hensher (1994) described the differences between a stated preferences and a stated choices experiment. In the first case, the individual is asked to indicate his/her preferences over a set of combinations of attributes in a rank-ordering or rating scale (Hensher, 1994). In stated choices experiments, the respondents choose one of the given combinations of attributes (Hensher, 1994). Another interesting fact is that in stated preferences experiments, the number of alternative attributes remains constant and only the attributes levels vary, while in stated choices experiments both the number of alternatives and attribute levels is possible to vary. (Hensher, 1994). The outcome from a stated preferences experiment can be a set of either rank-ordered preferences, or rating data, or choice responses. In ranking experiments, the respondent puts the alternatives in order based on his/her degree of preferences. In rating experiments, the designer of the survey gives to the respondents a (5-point to 10-point) Likert rating scale to express their degree of preference. In the last type of experiments (i.e. choice experiments), the individuals make decisions by comparing a set of alternatives and selecting the best one (Hensher, 1994).

To construct a stated preferences experiment, the researcher has to take some very important steps, which are defined in the study of Hensher (1994). The stated preferences experiment is a fully controlled experiment (Kroes and Sheldon, 1988; Hensher, 1994). The first step is related with the identification of the set of explanatory (or independent) variables and the specification of the mathematical form of utility functions. In the second step, the researcher selects the measurement unit of each of the independent variables. By using dummy or effects coding, non-continuous variables can be imported into the experiment. The specification of the number and the magnitude of the attribute value is accomplished in the third step. The fourth stage is related with the design of the survey. The researcher has to create combinations of attribute levels. There are several methods of designing a survey; the most important ones are: the full factorial and the fractional factorial design. The first type of survey design contains all the possible combinations of attribute levels. Fractional factorial design is able to reduce selectively the size of the experiments (Gunst and Mason, 2009). This type of designs are based on orthogonal tables, that ensure zero-correlation among the independent variables (Hensher, 1994). Yet, any interaction effect cannot be estimated if a fractional factorial design is selected to be developed, since there are significant correlations among interaction effects. The next step (5th step) is to translate all the different profiles (i.e. combinations of attribute levels) into a set of questions, that are contained in a survey form. If the number of profiles is quite high, then the researcher can create blocks of questions, that are going to be distributed to the respondents randomly. Pilot studies and face-to-face interviews with some of the future respondents can be performed before finalizing the survey form (Kroes and Sheldon, 1988). The sixth step is about the selection of the appropriate estimation procedure based on the type of obtained data (i.e. rank-ordered data, rating data and choice data) (Hensher, 1994). The final task is concerned with the use of the utility function parameters for calculating preferences or choice probabilities.

As it has been stated above, a stated preferences experiment will be conducted for the examination of important subjective notions of traffic safety, namely: perceived safety and driving. Previous paradigms from relevant studies, like: Wang et al. (2002) and Hill and Boyle (2007) that examined these concepts by asking car drivers, acted as a source of inspiration for the creation of a methodological tool. The study of Wang et al. (2002) was executed in roundabouts. The main explanatory variables were: the radius of the circle, number of circular lanes, visibility, traffic volume level, car speed and presence of pedestrians in crossings. An image from each of the selected were shown to the respondents. They rated the perceived safety of each driving situation in a 5-point Likert scale. Ordinal regression was executed for the estimation of perceived safety models in roundabouts. In the study of Hill and Boyle (2007), the respondents rated the driving stress in a 7-point Likert scale. Eighteen different hypothetical driving scenarios were presented to the respondents. Some examples of these hypothetical driving situations are: driving in an icy road, driving in heavy rain, driving behind a vehicle that is moving slower or braking, making a left turn, merging into heavy traffic, night driving etc (Hill and Boyle, 2007). For all the scenarios, the two researchers estimated driving stress models using proportional odds method (more in the section that follows). Explanatory variables were more related with the personal traits, namely: age, gender, number of crashes in the last ten years and whether or not the respondent commuted on a daily basis (Hill and Boyle, 2007). A stated preferences experiment for the development of a driving behavior model has never been conducted on pubic transport drivers, so far.

4.2. Regression with ordinal variables

As it has been argued in the previous paragraph, 7-point and 5-point Likert scales have been utilized in previous studies (Wang et al., 2002; Hill and Boyle, 2007) for the examination of subjective notions of traffic safety, such as: perceived safety and driving stress. The Likert scale is an ordinal scale;

therefore, the final form of data will be ordinal too. Although the responses are numerically labeled, the ordinal data, extracted from a stated preferences survey, does not have metric information (Liddell and Kruschke, 2018). In the ordinal scales, the set of the categories is very clear from the beginning; yet, the distances between the categories are not known. For example, the real numerical distance between a very unsafe (1) and a neutral (4) section may be much smaller than the distance between a neutral (4) and a very safe (7) section of a tram line. When metric models are applied to ordinal data, it is wrongly hypothesized that the intervals between the different response levels are equal, according to Liddell and Kruschke (2018). As it can be seen in figure 4.1, in the metric models, a normal distribution is utilized for the residual noise, while in the ordinal models, a thresholded commutative normal distribution is preferred.

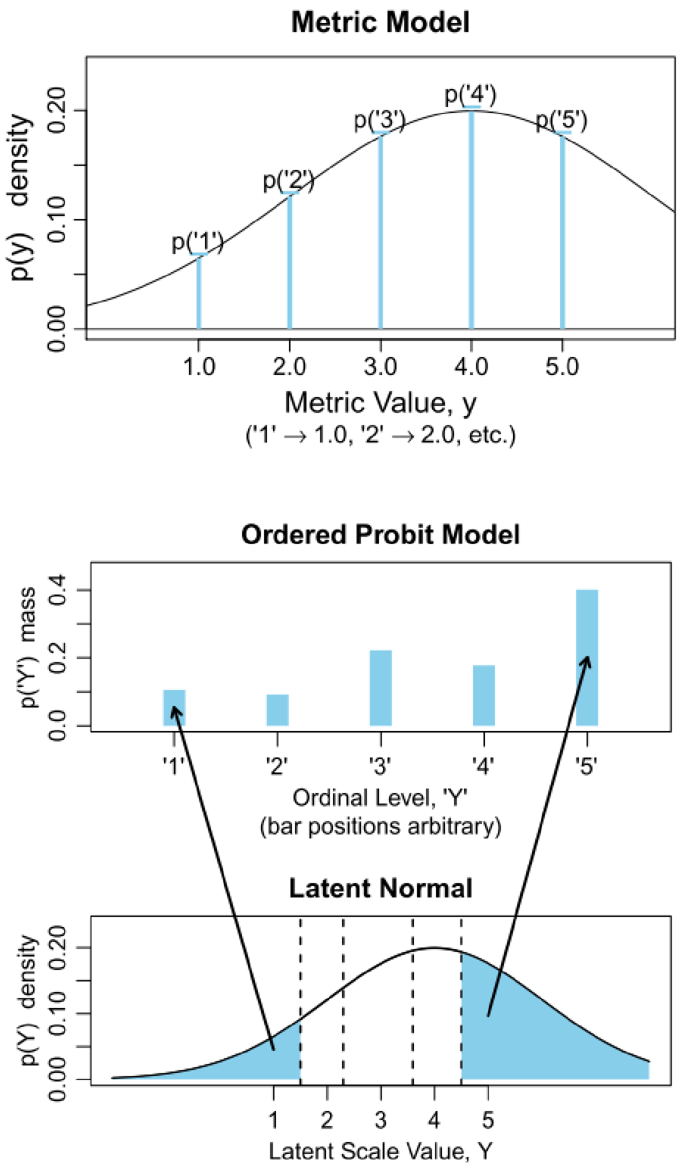

Figure 4.1: Metric model vs ordinal model
Source: Liddell and Kruschke (2018)

The ordinal scales differ from the nominal scales. Sometimes, nominal scales assign numbers as labels to categories in order to make the choice process easier (Scott Long, 2015). Yet, the options in this kind of choice experiments are not ordered. Ordinal scales utilize numbers to indicate a rank of a single attribute (Scott Long, 2015). Classic regression methods, like the probit, multinomial logit (MNL) and mixed logit (ML), have been used for the development of discrete choice models. For ordinal scales, the most commonly used methods are the ordered probit firstly developed by McKelvey and Zavoina (1975) and the ordered logit (or the proportional odds model) firstly developed by McCullagh (1980). Ordered logit can be considered an extension to the logistic regression, while the ordinal probit models assume that the error term is normally distributed. The general form of an ordinal model including both random and fixed beta parameters is:

$$y_{it}^* = \beta_i * x1_{it} + \mathrm{B} * x2_{it} + \varepsilon_{it} \tag{4.1}$$

$$y_{it} = \begin{cases} 1, & \text{if } -\infty < y_{it}^* \leq k_1 \\ \text{....} & \\ \text{....} & \\ j, & \text{if } k_{j-1} < y_{it}^* * \leq kj \\ \text{....} & \\ \text{....} & \\ J, & \text{if } k_{J-1} < y_{it}^* < +\infty \end{cases} \tag{4.2}$$

where:

y_{it}	= response t of individual i
y_{it}^*	= latent (dependent) variable
k_j	= threshold j
β_i	= random beta parameter
B	= fixed beta parameter
$x1_{it}, x2_{it}$	= values of independent variables x1 and x2
ε_{it}	= error term

In the ordinal models, the cumulative probabilities for each of the previously presented intervals (equation 4.2) can be computed by the following equations:

$$P(-\infty < y_{it}^* \leq k_1) = P(y_{it}^* \leq k_1) - P(y_{it}^* < -\infty) = P(y_{it}^* \leq k_1) + 0 = \\ = P(\varepsilon_{it} \leq k_1 - \beta_i * x1_{it} + \mathrm{B} * x2_{it}) = 1 - F(\beta_i * x1_{it} + \mathrm{B} * x2_{it} - k_1) \tag{4.3}$$

$$P(k_{j-1} < y_{it}^* \leq k_j) = F(\beta_i * x1_{it} + \mathrm{B} * x2_{it} - k_{j-1}) - F(\beta_i * x1_{it} + \mathrm{B} * x2_{it} - k_j) \tag{4.4}$$

$$P(k_{J-1} < y_{it}^* < +\infty) = P(y_{it}^* < +\infty) - P(y_{it}^* \leq k_{J-1}) = \\ = P(y_{it}^* > k_{J-1}) = F(\beta_i * x1_{it} + \mathrm{B} * x2_{it} - k_{J-1}) \tag{4.5}$$

The proportional odds assumption is one of the basic properties of an ordered logit model and the major difference between ordered logit and ordered probit models. According to this assumption, there is only one set of betas for all the different intervals (see equation 4.2). The interpretation of (linear) proportional odds models is much simpler compared to other (non-liner) ordinal models, according to McCullagh (1980). For a given dataset, the validity of proportional odds assumption can be tested by performing a X^2 test comparing a model using proportional odds assumption (null hypothesis) with one not using it. In order to interpret better the proportional odds assumption, the function of the odds (not the probability) of being less than or equal to j is given at the beginning.

$$\Omega(x)_{\leq j|>j} = \frac{P(y_{it}^* \leq j)}{1 - P(y_{it}^* \leq j)} = \frac{F(k_j - \beta_i * x1_{it} + \mathrm{B} * x2_{it})}{1 - F(k_j - \beta_i * x1_{it} + \mathrm{B} * x2_{it})} = \\ = \frac{\frac{\exp(k_j - \beta_i * x1_{it} + \mathrm{B} * x2_{it})}{1 + \exp(k_j - \beta_i * x1_{it} + \mathrm{B} * x2_{it})}}{1 - \frac{\exp(k_j - \beta_i * x1_{it} + \mathrm{B} * x2_{it})}{1 + \exp(k_j - \beta_i * x1_{it} + \mathrm{B} * x2_{it})}} = \exp(k_j - \beta_i * x1_{it} + \mathrm{B} * x2_{it}) \tag{4.6}$$

If the value of the variable $x2$ is increased by 1, then it is clear from the 4.6 that the odds will change. The odds ratio can be estimated, if we divide the odds after the change of $x2$ with the odds before the change of $x2$.

$$OR = \frac{\Omega(x2+1)_{\leq j|>j}}{\Omega(x2)_{\leq j|>j}} = \frac{\exp[k_j - \beta_i * x1 + \mathrm{B} * (x2+1)]}{\exp(k_j - \beta_i * x1 + \mathrm{B} * x2)} = \frac{1}{exp(B)} \tag{4.7}$$

The value of the odds ratio can be interpreted as: for a unit increase in $x2$, the odds of being in category less than or equal to j (compared to greater j) change by a factor $exp(-B)$, holding other variables constant (Scott Long, 2015). From the equation 4.7, it is clear that the odds ratio is the same for all j thresholds.

The marginal effects, that can be estimated from ordered models, are very useful in order to understand the contribution of each regressor to the final result (Scott Long, 2015). A marginal effect is given by the partial derivation of the probability with respect to $x2$ (or $x1$) (equation 4.8), if the $x2$ is a continuous variable (e.g. the number of pedestrians). If $x2$ is a categorical or dummy variable, the change of probabilities for a discrete change in $x2$ (holding other regressors constant) can be estimated by the equation 4.9

$$\frac{\partial P(y_{it} = j|x2)}{\partial x2} = B * f(B * x2_{it} - k_{j-1}) - B * f(B * x2_{it} - k_j) \tag{4.8}$$

$$\frac{\Delta P(y_{it} = j|x2)}{\Delta x2} = P(y_{it} = j|x = x2_{end}) - P(y_{it} = j|x = x2_{start}) \tag{4.9}$$

where:

$f(x)$	= the logistic PDF
$x2_{start}, x2_{end}$	= the starting and the ending value of variable $x2$

For the estimation of the fixed and the random beta parameters of perceived safety and driving stress, the Simulated Maximum Likelihood (SML) method is implemented. In the stated preferences experiment, each respondent will evaluate perceived safety and driving stress multiple times; thus, panel effects have to be taken into account. The estimation of models with panel effects allows the researchers to observe the heterogeneity in preferences and ”tastes”. Without the introduction of panel effects, each response is considered independent from the other responses of each individual. Hence, the dataset contains more pieces of information than it really does and the model finally underestimates the standard error of parameters. The heterogeneity in ”tastes” can be described properly in the random beta parameters distributions. The computation of ordinal models can be accomplished in R software. The additional package Rchoice developed by Sarrias (2016) has to be utilized in order to compute an ordinal model, that contains random beta parameters and panel effects. The joint probability function for the individual i can be calculated by the following equation:

$$f(y_i^*|x_i, \beta i, B) = \prod_{t=1}^{T}\prod_{j=1}^{J-1}[F(k_j - \beta_i * x1_{it} - B * x2_{it}) - F(k_{j-1} - \beta_i * x1_{it} - B * x2_{it})] \tag{4.10}$$

The integral of the previous pdf functions with respect the random beta parameter gives the joint pdf of all the individuals.

$$f(y_i^*|x_i, \theta, \mathrm{B}) = \int \prod_{t=1}^{T}\prod_{j=1}^{J-1}[F(k_j - \beta_i * x1_{it} - B * x2_{it}) - F(k_{j-1} - \beta_i * x1_{it} - B * x2_{it})] * g(\beta_i|\theta) * d\beta_i \tag{4.11}$$

The maximization of the previously presented function is accomplished through the Monte-Carlo simulation. In reality, the integral is computed by using random draws from the distribution $g(\beta_i)$ (Sarrias, 2016). The Halton draws method provides a better coverage per unit square than the pseudo-random draws method, as it can be seen in figure 4.2.

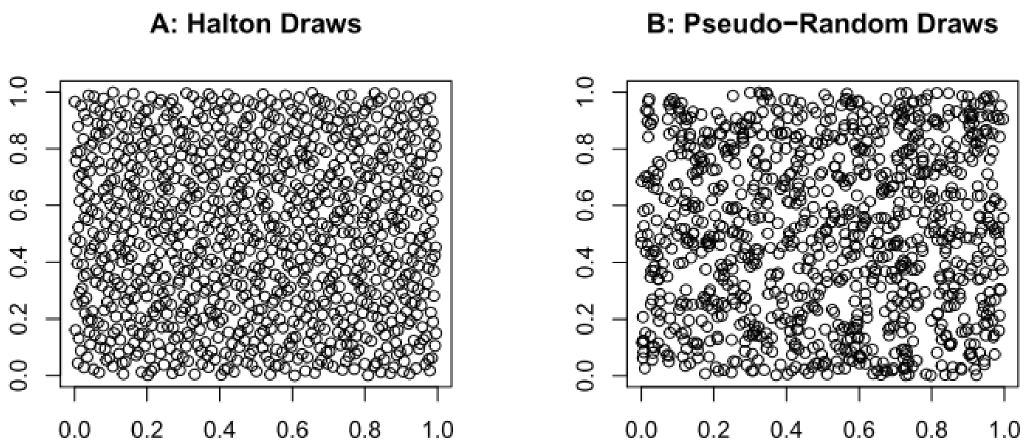

Figure 4.2: Halton draws vs pseudo-random draws
Source: Sarrias (2016)

Lastly, it has been proved (equation 4.12) that the introduction of an intercept in the model does not influence the beta parameter estimates, but the threshold estimates.

$$k_{j-1} < c + \beta_i * x1_{it} + \mathrm{B} * x2_{it} + \varepsilon_{it} \leq kj \Leftrightarrow k_{j-1} - c < \beta_i * x1_{it} + \mathrm{B} * x2_{it} + \varepsilon_{it} \leq kj - c \quad (4.12)$$

4.3. Black spot analysis

In relevant past studies (Zhixiao and Yan, 2008; Ha and Thill, 2011; Marti et al., 2016), the spots with high concentration of accidents, that sometimes are called ”black”, are indicated spatially through the utilization of the Kernel Density Estimation (KDE) tool. The classic planar KDE computes the density in the two-dimensional homogeneous Euclidean space, while the network KDE (an extension of planar KDE) computes the density in the one-dimensional space, as it is defined by the selected network. According to Ha and Thill (2011), the statistical technique of KDE is an approach that leads to intuitive visualization and exploration of data. Black spot analysis is also recommended by Marti et al. (2016) in the case of accidents that are not so frequent (e.g. tram accidents).

For the estimation of the planar Kernel density in each point of the grid two basic parameters are needed, namely: bandwidth (search radius) and kernel function (or k-function). Sometimes, different weights are attributed to each point of influence, according to a particular characteristic (e.g. accident severity). The generalized function of planar KDE is shown in equations 4.13 and 4.14.

$$\lambda(s) = \frac{1}{\pi * h^2} * \sum_{i=1}^{n} k(u_i) * w_i \quad (4.13)$$

$$u_i = d_{is}/h \quad (4.14)$$

where:

$\lambda(s)$ = the density at location s
h = the bandwidth or the search radius
$k(u_i)$ = the k-function
w_i = the weight according to a particular characteristic of point i
$d_i s$ = the Euclidean distance between point i and location s

The purpose of the Kernel function is to measure the so called ”distance decay effect” (Zhixiao and Yan, 2008; Mora-Garcia et al., 2015). Basically, the longer the distance between a point i and a location s is, the less that point is weighted for computing the overall density (Zhixiao and Yan, 2008). In literature, different forms of Kernel function have been utilized, such as the Rectangular, the Triangular, the Epanechnikov, the Bitweight (or Quartic) and the Triweight (Mora-Garcia et al., 2015).

The shape and the equation of each form is presented in figure 4.3. The Quartic function, which resembles the Gaussian function, is used in all the density estimations accomplished in this thesis.

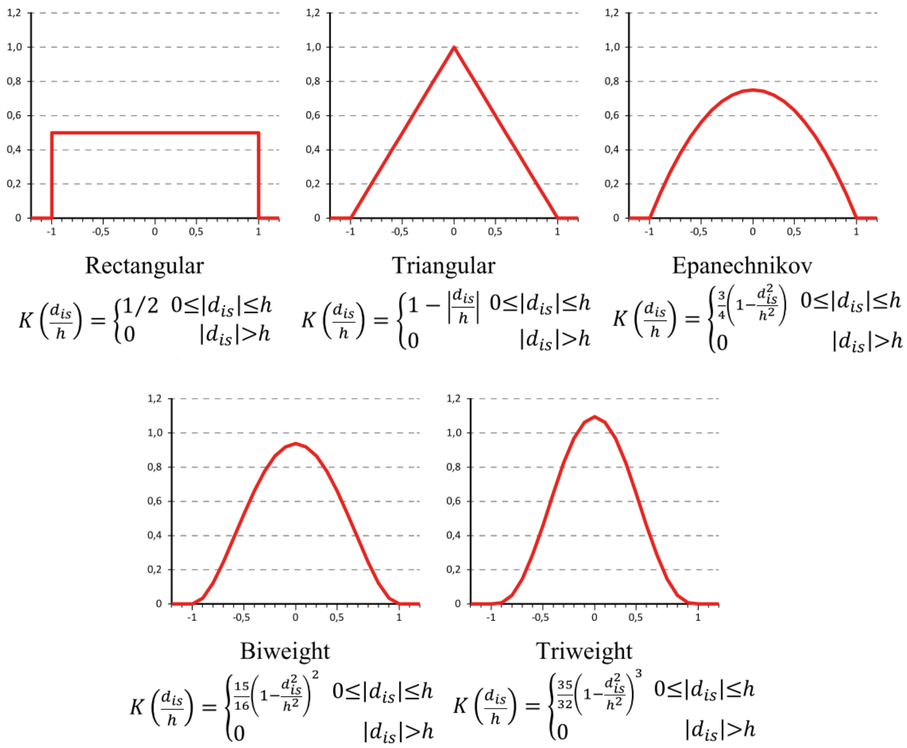

Figure 4.3: Kernel function forms
Source: Mora-Garcia et al. (2015); Own Elaboration, (2019)

The selection of the right bandwidths is surely not an easy process. Smaller search radius points out problematic roads or intersections, while larger search radius is useful for visualizing concentrations of accidents on a much larger scale, such as a city district (Ha and Thill, 2011). Another interesting approach is related with the introduction of weights in accidents according to their severity. In the study of Marti et al. (2016), victim equivalent (VE) values were introduced. A fatal accident was equal to 5 VE, an accident with severe injury(ies) was equal to 1 VE and an accident with minor injury(ies) to 0.2 VE.

Figure 4.4: Planar KDE vs Network KDE
Source: Ha and Thill (2011); Zhixiao and Yan (2008); Own Elaboration, (2019)

Zhixiao and Yan (2008) concluded that a planar KDE tends to over-detect clusters, as it searches for spatial patterns over the entire 2-D space. For example, the streets in the city centers are often denser than those at the outskirts; therefore, more accidents appear in a very close distance in the city centers (Zhixiao and Yan, 2008). The network KDE method differs from the planar KDE one in several aspects: the network space is used as the point event context and both search bandwidths and Kernel functions are based on network distance (Zhixiao and Yan, 2008). The equation of network KDE does not differ from the equation of planar KDE (equation 4.13). Yet, the differences in the final visualization of concentrations of accidents are quite obvious, as it can be observed, by comparing the output of the network KDE computed by Zhixiao and Yan (2008) and the output of the planar KDE computed by Ha and Thill (2011), in figure 4.4

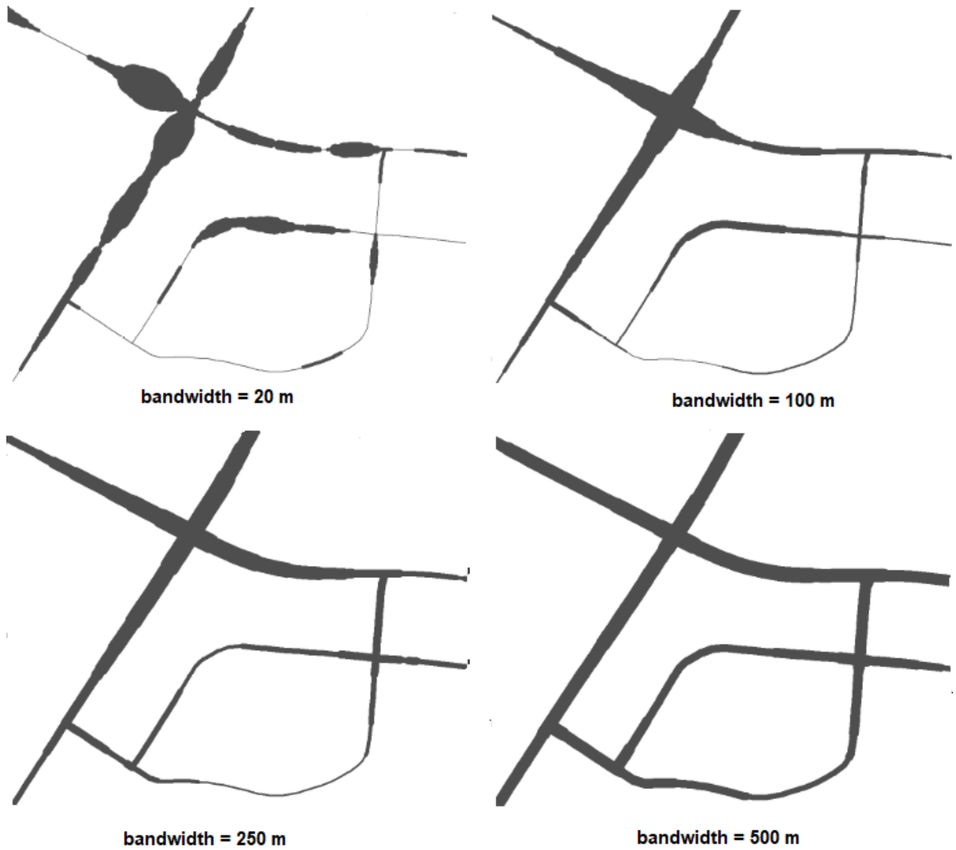

Figure 4.5: Network KDE using different bandwidths
Source: Zhixiao and Yan (2008); Own Elaboration, 2019

An important parameter for the network KDE is the maximum segment length (or lixel size). As Zhixiao and Yan (2008) have mentioned, larger lixel length effectively hides the detailed structures shown at fine resolutions. In this study, the size of the lixel is selected to be equal to 100 m. Furthermore, they have argued that narrow bandwidths (e.g. 20, 50 and 100 m) are able to produce patterns suitable for presenting local effects (or "hot spots"), while larger bandwidths are more suitable on larger spatial scales.

Although the equation of network KDE is similar to the equation of planar KDE, the estimation process of densities in networks is much more complicated. Specialized GIS-based software tools are required. In ArcGIS, the most popular tool is the SANET (Spatial Analysis on a Network); it was developed by a group of researchers at the University of Tokyo (Okabe et al., 2009). In the newest version of QGIS (i.e. QGIS 3.0), the network KDE can be executed through the use of the v.kernel.vector tool. One of the major problems of the previously mentioned GIS tool is that weights related with a characteristic of a point cannot be considered in the estimation process. Lastly, the output of both tools is a vector shapefile, while in the (classic) planar KDE, the output is a raster file.

4.4. Conclusions

In conclusion, the three main methodologies, namely: stated preference experiments, ordinal regression and black spot analysis, have so far been described in details.

The conduction of a stated preferences experiment is the only way in order to ”predict” perceived safety in different driving scenarios, since it cannot be measured in reality (Wang et al., 2002). The fluctuation of driving stress along a tram line can be indicated better by physiological data, such as: heart rate and skin response (De Waard, 1996; van Gent et al., 2018); yet, the estimation of driving stress models by doing a stated preferences experiment is an alternative and less time-consuming approach. By following this approach, some of the driving scenarios, which are contained in the survey form, are likely to be imaginary. Therefore, driving stress and perceived safety is rated in a plethora of cases. According to Hensher (1994), the steps for the design of a stated preferences experiment are: identification of independent variables, selection of the measurement unit of each independent variable, specification of variable levels, experiment design, development of survey form(s), selection of an appropriate estimation procedure and estimation of preference probabilities.

In the previous studies of Wang et al. (2002) and Hill and Boyle (2007) the respondents rated perceived safety and driving stress in a 5-point and 7-point Likert scales, respectively. Likert scales ”produce” ordinal data. Ordered logit and ordered probit are the main techniques for estimating models with ordinal data (Hensher, 1994). By adding the thresholds of each interval as additional unknown parameters in the estimation process, the distances between the categories of the ordinal scale can be computed. One of the main characteristics of ordered logit is the existence of proportional odds. It means that for all the estimated intervals, there is only one set of beta parameters (McCullagh, 1980; Scott Long, 2015). The introduction of random explanatory variables allows the computation of the heterogeneity in ”tastes” among the individuals. Random variables are very important in the estimation of models, that are related with subjective notions, such as perceived safety and driving stress. The Simulated Maximum Likelihood (SML) is the main method for the computation of ordered models with random effects. In essence, it is a Monte-Carlo simulation, which utilizes random draws from known distributions.

Black spot analysis was selected for the examination of objective safety. According to Zhixiao and Yan (2008), it can reveal some interesting spatial patterns of past accidents. The black spot analysis is accomplished in GIS by using Kernel Density Estimation (KDE) algorithms. The classic planar KDE computes the density in the two-dimensional homogeneous Euclidean space, while the network KDE computes the density in the one-dimensional space. The bandwidth and Kernel function are the two parameters that should be selected in the beginning of the estimation process. The purpose of the Kernel function is to measure the so called ”distance decay effect”. It means that the longer the distance between a point i and location s is, the less that point is weighted for computing the overall density (Zhixiao and Yan, 2008; Mora-Garcia et al., 2015). Smaller bandwidths can be used for specifying problematic tram sections or crossings, while bigger bandwidths are more suitable for the examination of tram safety problems on a larger scale (Zhixiao and Yan, 2008). Weights related to the severity of a tram accident can be introduced in the planar KDE. Until now, there is no developed algorithm for computing weighted network KDE. Yet, for the examination of the spatial patterns or past crashes, network KDE should be preferred instead of planar KDE. According to Zhixiao and Yan, (2008), the planar KDE tends to over-detect clusters, as it searches for cluster patterns over the entire 2-D space.

5

Data Collection

The objective of this chapter is to determine the scientific techniques for collecting data useful for estimating statistical models and trends. First of all, the analyses of this thesis are performed in two European tram networks (i.e. Athens and Amsterdam), that are selected as study cases. Therefore, all the collected data should concern these networks only. A stated preferences experiment is designed for collecting ratings of perceived safety and driving stress of the tram drivers of Athens. These ratings should be connected with important variables, such as: alignment type, existence of crossings or stations, volume of VRUs and delay, in order for significant correlations to be computed in the next stage. The collection of reported accidents that have occurred in Amsterdam or in Athens is important in the analysis of objective safety. Additional pieces of information, such as the accident severity, should be known to examine additional dimensions of traffic safety, such as consequences. Spatial data from the study tram networks (like: locations of tram stops, attraction poles, alignment type, location and type of pedestrian/cyclign crossing) can support the survey design. Moreover, they will be useful in uncovering noticeable statistical trends and spatial patterns of tram crashes.

5.1. Study Cases

Two European tram networks are selected as study cases, namely: the tram network of Athens (Greece) and the one of Amsterdam (the Netherlands). In the first network, analyses about perceived safety and driving stress are conducted. In the network of Amsterdam, accident records are utilized for the examination of objective safety. In the next paragraphs, the characteristics of the study networks are presented in detail.

5.1.1. Athens

The length of the tram network of Athens is 30.90 km. The tram operations in Athens started in March 2004. The transport operator of the network is STASY. Compared to the other tram networks of the European capitals, the Athenian tram network is quite new and small.

The total number of tram routes is 3. The first route (Syntagma-SEF) connects the city center (i.e. Syntagma square) with the area of Neo Faliro. The city center is also connected with the southeast districts, such as Alimos, Elliniko and Glifada, through the second tram line (Syntagma-Asklipeio Voulas). The third tram line (Asklipeio Voulas-SEF) runs along the beach of the metropolitan area of Athens. The total number of the present tram stops is equal to 50. Figure 5.1 shows the tram network of Athens. In addition, an online map presenting the Athenian network has been developed; the link and the user guidelines are given in the Appendix B.

In Piraeus, which is the port of Athens, a new tram section has been constructed; the tram operations are expected to start in December 2019. It is a loop, which starts from the existing terminal called SEF and ends at the same point. The length of the new section is 5089.75 m and 12 new tram stops are located there. On the other hand, the operations from Neos Kosmos to Syntagma stopped in November 2018 due to maintenance works and are likely to start again in December 2019. The total length of the closed section is 2965.20 m. In the past, many different plans for extending the tram network from Syntagma to other central squares and boulevards of Athens have been developed.

In the majority of the urban streets, the tram track is semi-exclusive and is located in the middle of the street. Indeed, in 14.88 out of 30.90 km (48.15%), the previously mentioned alignment type appears. There are cases in Athens, where the semi-exclusive alignment is not in the middle of the street but near the sidewalk. This alignment type is observed in the sections that are located next to the beach. The total length of semi-exclusive alignments near the sidewalk is 8.26 km (26.75%). By integrating the new section located in Piraeus in the length calculations, the share of mixed traffic alignments is 18.25% (5.64 km). In addition, the tram track is fully shared with pedestrians in 2.12 out 30.90 km (6.86%). As it can be seen in figure 5.1, the new tram section consists only of non-exclusive alignments. Indeed, in the 49.53% of the new section, the tram track is shared with pedestrians, while the remaining 50.46% is shared with the motorized traffic.

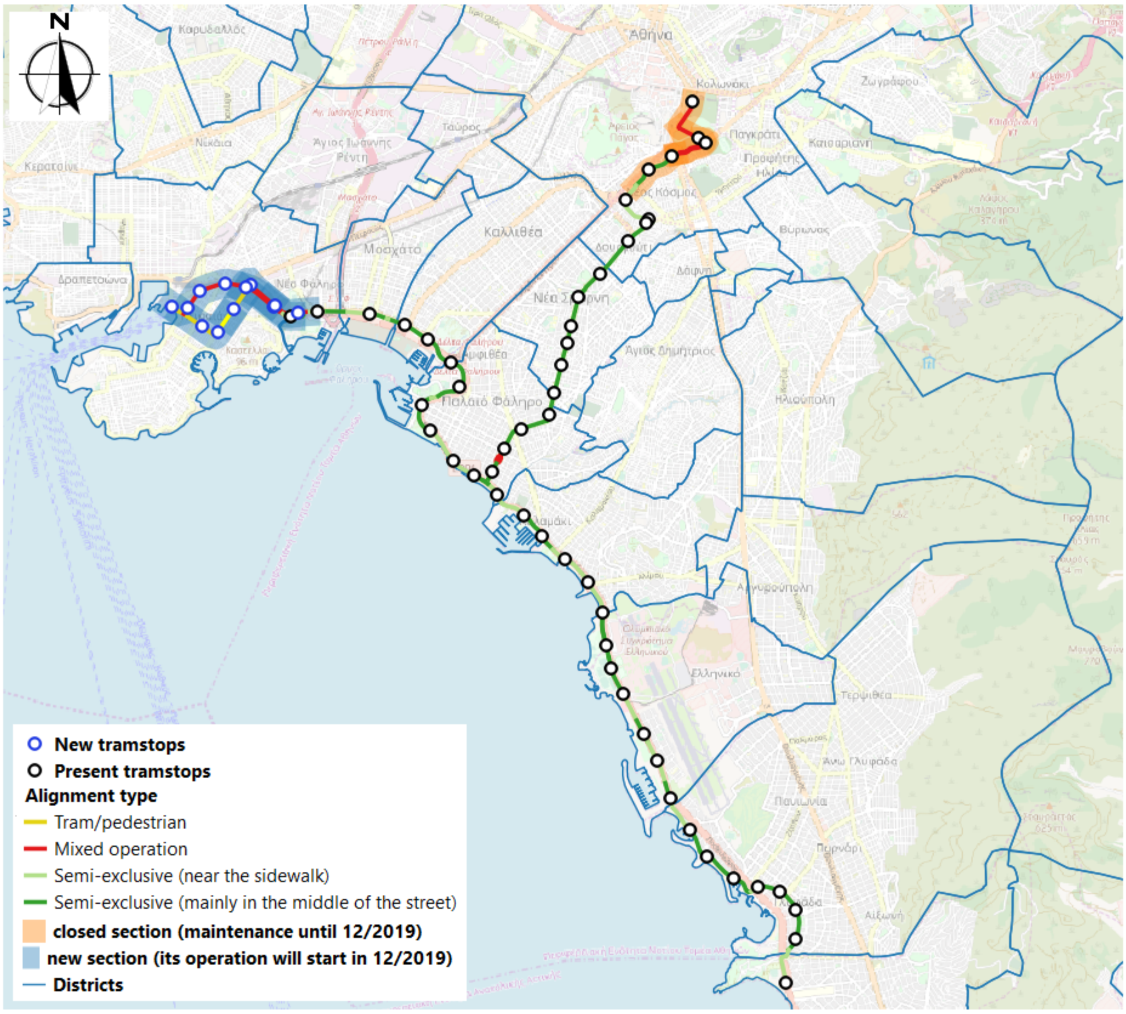

Figure 5.1: The tram network of Athens, Greece

The previously mentioned facts are some of the key reasons why the tram network of Athens was included in the analysis. As it will be proved in the next steps, tram drivers of Athens are very experienced in driving in semi-exclusive alignments. The new section, as it was designed, will bring up new challenges and difficulties, which have not been faced in the past. Hence, additional parameters, like route familiarity, which may affect perceived safety and driving stress, can be examined in Athens. Furthermore, in the stated preferences survey, the tram safety of the new section in Piraeus is being assessed for the first time. The safety conditions between the present section and the new section can be compared in this analysis. Lastly, the volume of pedestrians is expected to be higher in Piraeus in comparison with the majority of the urban space, at which the tram is operating now. Definitely, this last fact creates an ideal "scene" for analysing the safety of VRUs along the tram lines.

5.1.2. Amsterdam

In comparison with the tram network of Athens, the network of Amsterdam is older and bigger (in terms of length). Its length is estimated to be equal to 96.67 km. It has been operated by the public transport company Gemeentelijk Vervoerbedrijf (GVB) since 1943. The total number of current tram routes is 14. Most of these routes connect the city center and specifically the central train station (Amsterdam Centraal) with important districts of Amsterdam, such as Osdorp, IJburg, Nieuw Sloten, Sloterdijk, Diemen and Amstelveen. There are 183 tram stops in the metropolitan area of this city and some of them are connected with the metro or national train stations. Figure 5.2 presents the tram network of Amsterdam and in the Appendix B, the link for the online map is given. In the next stages a spatial analysis for the examination of objective safety in the tram network of Amsterdam is conducted.

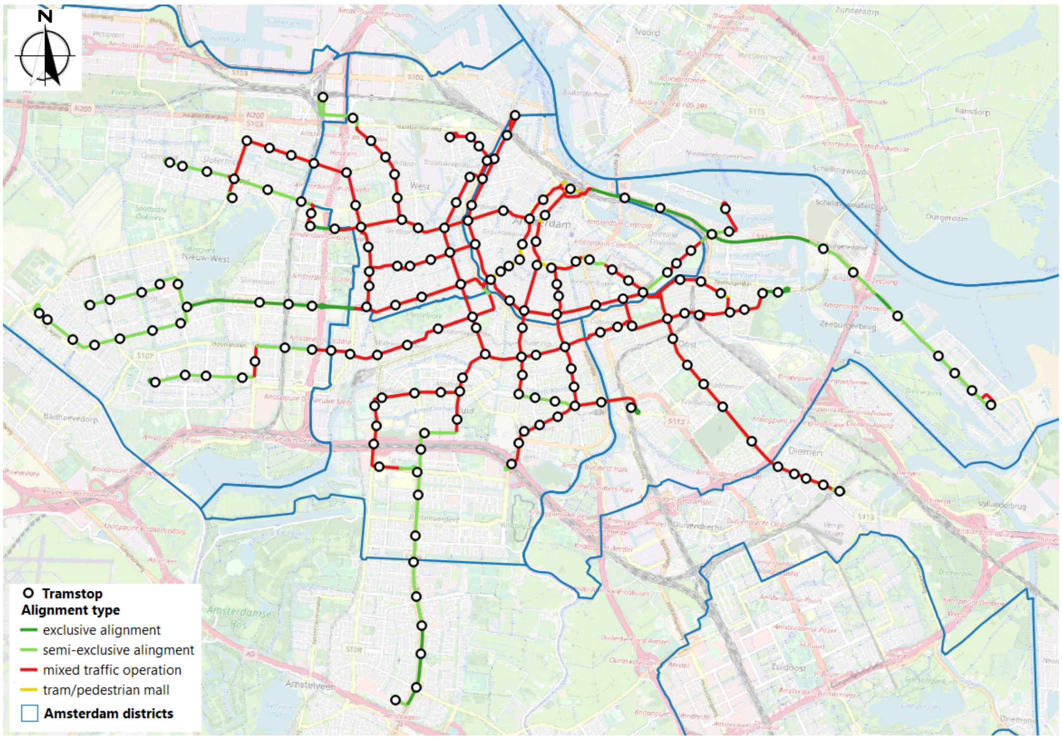

Figure 5.2: The tram network of Amsterdam, the Netherlands

Four types of alignments are observed in the tram network of Amsterdam, namely: exclusive, semi-exclusive, mixed traffic operations and tram/pedestrian malls. Exclusive alignments are seen in the roads: Beneluxbaan, Piet Heinkade, and Cornelis Lelylaan. In addition, in the tram line 26 Centraal Station-IJburg, there is a tunnel (Piet Heintunnel) and a brigde (Enneus Heerabrug), on which the tram runs separately from the motorized traffic. The total length of exclusive alignments is 10.32 km (10.68%). Semi-exclusive alignments are observed in the outskirts of Amsterdam, like Osdrop or Amstelveen. The total length of semi-exclusive alignments is estimated to be equal to 23.60 km (24.21%). In 60.60 out of 96.67 km (62.70%), the tramway is shared either with buses or with the motorized traffic. Mixed traffic alignment is definitely a very common design inside the Centrum (i.e. the central district of Amsterdam) and in the areas around it. Tram pedestrian malls exist only in two streets: Leidsestraat and Singel and in some significant squares: Stationplein, Dam square, Rembrantplein and Leidseplein. The total length of tram/pedestrian malls is 2.13 km (2.20%). The tram network of Amsterdam has 590 pedestrian and cycling crossings; most of them (i.e. 75.94%) are protected by traffic lights.

The existence of a complete set of accidents records available on an online database was one of the main reasons why Amsterdam was selected for the examination of objective safety. Compared to other European networks, the study tram network has a wide variety of different designs. Furthermore, Amsterdam is a city with very high cycling and pedestrian flows, especially inside the city center. In addition, in the tram network of Amsterdam, there are many crossing points. Hence, tram safety, especially in sections of Amsterdam where many and complex interactions between VRUs and trams occur, is on its own a very interesting topic for research.

5.2. Survey Design

In this section, the stated preferences experiment, which will examine perceived safety and driving stress in the tram network of Athens, is designed. The steps, which were described in the section 4.1, are followed in order to create a useful methodological tool, that can help the collection of data related with the subjective notions of tram safety. Further details regarding the choices made in each step of the survey design are given in the next paragraphs.

5.2.1. Dependent variables

The dependent variables of the developed utility functions (see equations 5.1, 5.2 and 5.3) are: the perceived safety in the first model and the stress levels of tram drivers in the second model. Therefore, in the first phase, the respondent answers the question of how safe he/she would feel, while he/she is driving in the presented sections, by rating from 1 (very unsafe) to 7 (very safe). To answer the second question, about how much stress he/she would feel, while he/she driving in the same section, the tram driver gives a grade from 1 (not stressful at all) to 7 (very stressful).

	Name	**Symbol**	**Levels**						
Y.1	Perceived safety	psafe	**Very unsafe (1)**	2	3	**Neutral (4)**	5	6	**Very safe (7)**
Y.2	Stress levels	stress	**Not stressful at all (1)**	2	3	**Moderate stress (4)**	5	6	**Very stressful (7)**

Table 5.1: Dependent variables and Likert scales

According to Joshi et al. (2015), a 7-point Likert scale, which is used in this study, provides enough options, that are closer to the original view of the respondent and reduces the role of ambiguity in the responses compared to a 5-point scale. The above researchers have also mentioned that the human mind is able to distinguish 7 categories at a time and adding more categories, such as a 10-point scale, may create confusion to the respondents. As it has already been presented, Hill and Boyle (2007) provided a 7-point scale to the respondents for the assessment of driving stress, while Wang et al. (2002) preferred a 5-point scale. Joshi et al. (2015) mentioned that one of the major problems of using Likert scales in the scientific research is whether the given options are equivalent and equidistant. Ordered probit and ordered logit are the methods that can solve this problem. The six thresholds of the 7-point Likert scale are introduced in the model computation as additional unknown parameters.

Table 5.1 presents the dependent variables and the Likert scales that are going to be used in the survey. As it can be interpreted by observing the colors of the cells, there is an inverse relationship between these two scales. For example, a tram section, that is rated as very unsafe (1), is likely to be evaluated as very stressful (7) at the same time. This inverse relationship may create confusion to the respondents. Yet, there is a match between the two Likert scales and the two questions, which are going to be answered by the respondents, namely: (1) how safe would you feel and (2) how much stressed would you feel.

5.2.2. Independent variables and variables levels selection

For the determination of the independent variables of perceived safety and stress levels of drivers, knowledge from past research papers, such as: Naznin et al. (2017) is utilized. The problem was that tram companies considered the procedure of conducting both a qualitative (interviews) and a quantitative study (i.e. questionnaire form) to be very "heavy", in terms of cost and time, in a small period of 6 months.

There are multiple sets of variables related with perceived safety. Figure 5.3 presents all the potential independent variables. The first set is about the characteristics of the individuals, such as gender, age and experience. The second and more relevant (to this study) group is about the design of the tram alignments and features (i.e. crossings and tram stops) that comes together with it. Design consistency can also be considered an independent variable of stress. Multiple driving conditions appear in the road environment. Variables like the weather, light and visibility can affect driving performance and consequently perceived safety. In the conditions group, variables related with the level of traffic volumes are included as well. In the study conducted by Naznin et al. (2016), the correlation between objective safety (i.e. the number of fatal accidents) and characteristics of the tram vehicle (i.e. floor, age and length) were proved statistically significant for a 95% confidence interval. Lastly, there are parameters, which are related with tram operations. The arrival delay, the load of standing passengers inside the vehicle cabin, the load of waiting passengers in a tram stop and the fatigue, all add extra pressure to the drivers according to figure 2.5. On the contrary, the average speed is more closely connected with perceived safety (Naznin et al., 2016).

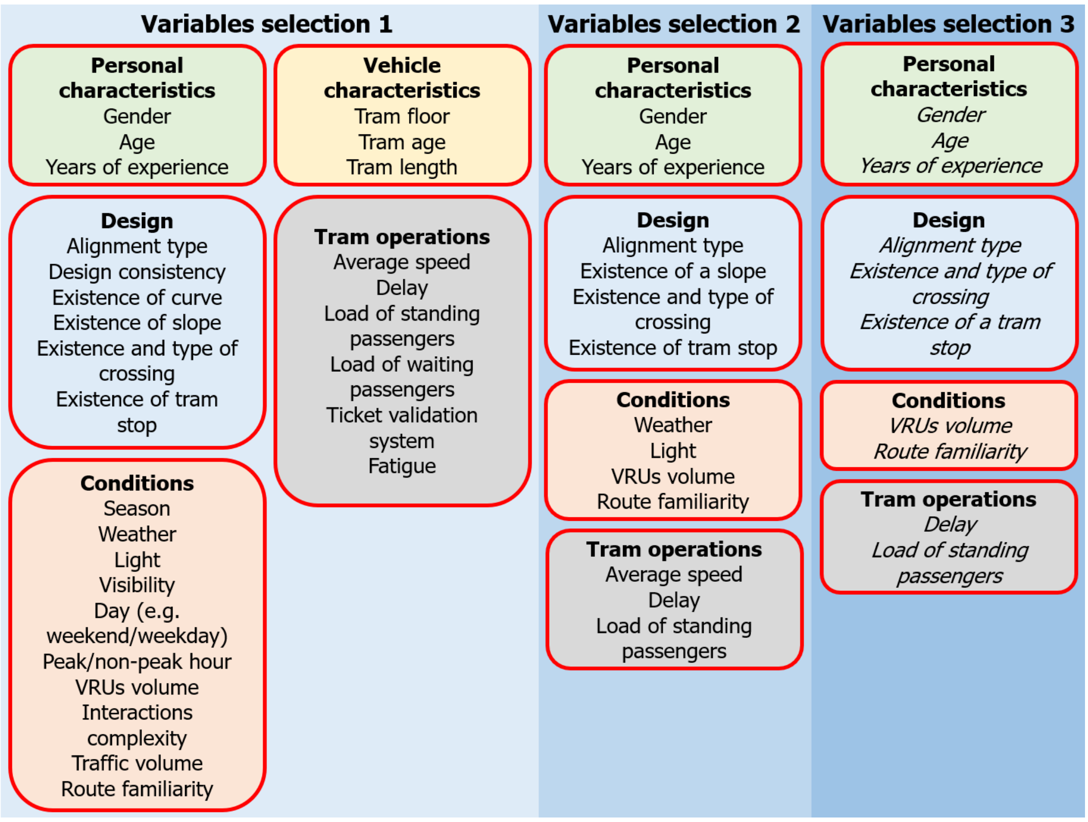

Figure 5.3: Selection of independent variables

A big number of independent variable results in a bigger number of hypothetical scenarios, which should be rated by the tram drivers. Some of the previously mentioned variables should be excluded from the stated preferences survey. The characteristics of the rolling stock differ among the tram networks of the world. Some tram companies use one type of rail vehicles (e.g. Athens) and some others use many different types (e.g. Melbourne and Amsterdam). In addition, examining the contribution of rail vehicle characteristics to perceived safety would not provide significant additional knowledge regarding the research objectives, which refer to the examination of perceived safety and driving stress in mixed traffic operations. Another variable that was excluded is the existence of a curve. In reality, visibility problems have been observed in urban segments with curves. An image, which will describe each scenario, is definitely not enough to present clearly the visibility problems. Maybe a video or a live image of each driving situation would prove more useful, though it is difficult to collect them if you are not inside the cabin of the driver. The variable of season is correlated with the weather and the dummy variables of day and peak hour are correlated with the traffic volumes. Since this thesis focuses on the interactions between VRUs and trams, only the volume of VRUs is taken into account in the final models. In addition, the complexity of these interactions is mainly connected with the alignment type. If the tram infrastructure is fully shared with pedestrians, the latter have more freedom to move and the interactions are much more complex compared to a semi-exclusive alignment, where the pedestrians are encouraged by the design to use the crossings. In the set of variables related with tram operations, fatigue is a very significant independent variable of stress. Yet, this factor could not be included in the survey, since drivers would use the survey in order to address complaints about the schedules and the working hours. Lastly, the load of waiting passengers and the ticket validation were considered insignificant parameters from the beginning.

More parameters are discarded in order to determine the final set of independent variables. In practice, it is very hard to collect many images with different weather and light conditions, not to mention that it requires a lot of time. Furthermore, it is well known in the literature that on rainy days and at nights, driving is subjectively and objectively more dangerous. Moreover, the existence of a downhill has a significant impact on safety; yet, the network of Athens does not have many of them. In addition, it would be difficult to find tram sections in the entire network with slopes and different design characteristics (i.e. a section with slope and semi-exclusive alignment, a section with slope and mixed traffic operation...etc). Lastly, the speed limits are related with the design of each tram section and tram drivers usually adopt the speed of the rail vehicle based on the movements of VRUs.

Index	Variable name	Symbol	Number of levels	Levels				Presentation
	Independent variable connected with individual characteristics							
G.1	Gender	**gen**	2	Male	Female			
G.2	Age Group	**age**						
G.3	Experience	**expe**	3	More than 15 years	Between 3-15 years	Less than 3 years		
	Indepenent variables connected with perceived safety							
A.3	Alignment type	**align**	4	1: Tramway shared with pedestrians	2: Mixed traffic operations	3: Semi-exclusive (near the sidewalk)	4: Semi-exlusive (in the middle of the street)	in picture + map + text
A.4	Pedestrian Crossings	**pcrs**	2	1: Without pedestrian crossing	2: With unprotected pedestrian crossing (without traffic lights) in the next 50 m	3: With protected pedestrian crossing (with traffic lights) in the next 50 m		in picture + text
A.5	Station existence	**sts**	2	1: With a station in the next 50 m	0: Without a station in the next 50 m			in picture + text
A.6	Volume of VRUs	**vru**	3	1: Level C: >20 VRUs	2: Level B: 10-20 VRUs	3: Level A ≤10 VRUs		in picture + text
	Extra independent variables connected with stress levels							
B.1	Arrival Delay	**time**	3	1: High scenario: 25 mins delay	2: Medium scenario: 15 mins delay	3: Low scenario: 5 mins delay		with text
B.2	Load of passengers	**load**	3	1: High Scenario: standing passengers = 100% * standing capacity	2: Medium Scenario: standing passengers = 50% * standing capacity	3: Low Scenario: standing passengers: = 0% * standing capacity		with text
B.3	Familiarity	**fam**	2	0: Unfamiliar	1: Familiar section			

Table 5.2: Independent variables and variables levels

As it can be seen in figure 5.3, in selection 3 column presented with italic letters, the set of independent variables has been finally selected; therefore, the next step is the determination of the variable levels. Taking into account the basic classification developed by Korve et al. (1996), the different segments of the tram network of Athens can be classified into 4 types of tram alignments, namely: tramway shared with pedestrians, mixed traffic operations, semi-exclusive alignment near the sidewalk and semi-exclusive alignment in the middle of the street. Furthermore, there are spots with unprotected crossings (i.e. without traffic lights) and spots with protected crossings. Only one type of stations (i.e. super stop) appears in the network of Athens. For the variable related with the volume of VRUs, it was decided that it would be described by three volume levels that are presented in figure 5.5. Before the pilot study, the high, medium and low level of delays were selected to be equal to 10, 5 and 2.5 minutes respectively. After the pilot study and by consulting the managers of STASY, the previously mentioned delays increased by 2.5, 5 and 15 minutes respectively (more details about the pilot study in the sub-chapter 3.1.6). The load of standing passengers will be expressed in the survey form with proportions of tram standing capacity. In the low level, there are no standing passengers and in the high level, the number of standing passengers is equal to the capacity. Lastly, tram drivers of Athens are not familiar with the section located in Piraeus.

Table 5.2 presents all the independent variables and their levels by taking into account the special characteristics of the tram network of Athens. With some small modifications, for example in the type of alignments or in the levels of arrival delay, this tool can easily become suitable for different networks of the world.

5.2.3. Model equations

For the estimation of the models, categorical variables such as: the alignment type, the pedestrian crossing and station existence are treated as dummy variables. The use of dummy coding is useful in models that describe preferences, because, for example, the contribution of a tramway shared with pedestrians to perceived safety may differ significantly compared to the contribution of a semi-exclusive alignment. The dummy coding scheme of all the categorical variable is presented in table 5.3.

	align1	align2	align3	pcrs1	pcrs2	sts	gender	expe1	expe2	fam
Tram/pedestrian mall	**1**	0	0							
Mixed traffic operation	0	**1**	0							
Semi-exclusive 1	0	0	**1**							
Semi-exclusive 2	0	0	0							
Without crossing				**1**	0					
With unpotected crossing				0	**1**					
With protected crossing				0	0					
With station						**1**				
Without station						0				
Male							**1**			
Female							0			
Less than 3 years								**1**	0	
3 to 10 years								0	**1**	
More than 10 years								0	0	
Familiar										**1**
Unfamiliar										0

Table 5.3: Dummy coding of categorical variables

The relationship of perceived safety (dependent variable) with 1) the alignment type, 2) the existence of a station (or tram stop), 3) the existence and the type of pedestrian crossing and 4) the number of vulnerable road users in the road environment (independent variables) is examined in the first model (equation 5.1). Additional variables related with the individual characteristics can be gender, age and experience. In the tram network of Athens, tram drivers are completely unfamiliar with the new tram section of Piraeus. The parameter of familiarity may influence the perceived safety and the stress levels of drivers; but it is correlated with the existence of a tram/pedestrian mall ($R^2 = 0.57$) or mixed traffic alignment ($R^2 = 0.57$). Therefore, it cannot be added in the perceived safety model; in the stress model, it can be imported only instead of the perceived safety variable.

$$psafe = \beta_{align1} * align1 + \beta_{align2} * align2 + \beta_{align3} * align3 + \beta_{pcrs} * pcrs + \beta_{sts} * sts + \beta_{vru} * vru + \varepsilon \quad (5.1)$$

where:

$psafe$	= perceived safety
$\beta_{align1}, \beta_{align2}, ..., \beta_{vru}$	= beta parameters
$align1, align2, align3$	= dummy variables related with alignment type
sts	= dummy variable related with station existence
$pcrs1, pcrs2$	= dummy variables related with pedestrian crossings
vru	= volume of VRUs in the road environment
ε	= error term

Perceived safety is considered to be one of the factors of driving stress. Stress is not only related with safety, but it is also related with "more operational" factors, such as the arrival delay and the load of standing passengers. There are two ways to formulate the equation of stress levels. The first way (equation 5.2) is by introducing an extra independent variable, which is perceived safety, as it can be estimated by the previous perceived safety model. A different formulation is to import all the independent variables of perceived safety in the model related with driving stress (equation 5.3). In the first case, the contribution of perceived safety to the pressure felt by the drivers can be computed, while the second one provides more evidence regarding the impact of the characteristics of the road environment on driving stress. Lastly, in all the above models, all the beta parameters are selected to be random in order to examine heterogeneity in "tastes" of individuals (more details in the sub-chapter 3.1.7).

$$stress = \beta_{psafe} * psafe + \beta_{time} * time + \beta_{load} * load + \varepsilon \tag{5.2}$$

$$stress = \beta_{align1} * align1 + \beta_{align2} * align2 + \beta_{align3} * align3 + \beta_{pcrs} * pcrs + \beta_{sts} * sts + \\ + \beta_{vru} * vru + \beta_{time} * time + \beta_{load} * load + \varepsilon \tag{5.3}$$

where:

$stress$ = driving stress
$time$ = arrival delay in minutes
$load$ = load of standing passengers expressed in percentages of the total standing capacity

5.2.4. Development of online forms

The list of the independent variables and their levels are given in the table 5.2. Among the scenarios, the factors that vary are: the alignment type, the existence of pedestrian crossing and station, the volume of VRUs, the arrival delay and the load of standing passengers. Familiarity cannot vary, because, in the tram section of Piraeus, there are no semi-exclusive alignments. So an unfamiliar semi-exclusive section cannot be found in the network of Athens. The total number of combinations (scenarios) would be $4 * 2 * 2 * 3 * 3 * 3 = 432$ if it had been decided to develop a full factorial design. Grading 432 cases would be a tedious and boring process for the tram drivers. As it has been mentioned in the previous chapters, fraction factorial designs are able to reduce selectively the size of the experiment without adding correlations among the independent variables. The equation 5.3 has been introduced in the estimation process of the orthogonal table. As it can be seen in the orthogonal table 5.5, the number of combinations (scenarios) are reduced (equal to 36). In table 5.4, it is clear that there is no correlation between the independent variables. The 36 scenarios are divided into 3 blocks (i.e. 12 scenarios in each one) in order to make the rating process less boring for a driver. In addition, from the beginning, the author consulted the thesis supervisors and decided to create a 10-minute survey form in order to facilitate the process of finding a tram company that will be willing to cooperate in this research.

	align	*sts*	*pcrs*	*vru*	*time*	*load*	*block*
align	1						
sts	0	1					
pcrs	0	0	1				
vru	0	0	0	1			
time	0	0	0	0	1		
load	0	0	0	0	0	1	
block	0	-0.06804	0	-0.04167	-0.04167	0	1

Table 5.4: Correlations among independent variables

The survey form was uploaded on the internet and the respondents could fill it either by desktop/laptop or by smartphone/tablet. In the first page of the survey, tram drivers are informed about the purpose of the survey, the time they need to fill it and the type and number of questions they have to answer to. There are also three important notifications; the first one urges the driver to focus only on the VRUs presented in the pictures, the second one informs them that in all cases, the speed of the rail vehicle is lower than or equal to the speed limit, and the last one asks them to assume that they are driving in the morning and it is not raining. In figure 5.4, a single page from the questionnaire form is given. At this point, it should be mentioned that the complete survey form of block 1 is in the Appendix A. At the top of the page, pieces of information about each scenario are provided. The respondent is able to click in the link to see the exact location of each scenario on an online map developed by the author (more about online maps in Appendix C). Therefore, the respondents know very well the location of the image before rating the perceived safety. Next, the image is presented to the tram driver.

scenario	align	sts	pcrs	vru	vru_num	time	load	fam	block
1	1	1	2	2	12	1	1	0	1
2	1	1	3	3	1	2	2	0	2
3	1	1	1	1	26	3	3	0	3
4	3	0	3	2	17	3	2	1	1
5	3	0	1	3	1	1	3	1	2
6	3	0	2	1	30	2	1	1	2
7	2	0	1	1	24	3	3	0	3
8	2	0	2	2	11	1	1	0	3
9	2	0	3	3	1	2	2	0	2
10	3	0	2	1	30	2	1	1	1
11	3	0	3	2	17	3	2	1	3
12	3	0	1	3	1	1	3	1	3
13	2	1	3	1	23	1	3	0	3
14	2	1	1	2	10	2	1	0	2
15	2	1	2	3	3	3	2	0	1
16	4	1	2	3	3	3	2	1	1
17	4	1	3	1	28	1	3	1	3
18	4	1	1	2	15	2	1	1	2
19	4	1	2	3	3	2	3	1	1
20	4	1	3	1	28	3	1	1	2
21	4	1	1	2	15	1	2	1	2
22	4	0	3	2	12	2	3	1	1
23	4	0	1	3	0	3	1	1	3
24	4	0	2	1	22	1	2	1	3
25	1	1	1	3	1	3	1	0	3
26	1	1	2	1	24	1	2	0	2
27	1	1	3	2	12	2	3	0	1
28	1	0	1	1	24	2	2	0	1
29	1	0	2	2	15	3	3	0	2
30	1	0	3	3	2	1	1	0	3
31	3	1	1	2	11	1	2	1	1
32	3	1	2	3	4	2	3	1	3
33	3	1	3	1	21	3	1	1	1
34	2	0	3	3	1	1	1	0	2
35	2	0	1	1	24	2	2	0	1
36	2	0	2	2	11	3	3	0	2

Table 5.5: Tram driving scenarios

Underneath the picture there is a text, where the variable values are described. In the majority of scenarios, the text confirms the pieces of information presented in the pictures. One exception occurs when the scenario has a protected crossing instead of an unprotected one. Since the number of protected tram crossings is limited in Athens, it is asked from the drivers to assume that the crossing that appears in the image is now protected. Additional pieces of information related with the arrival delay and the load of standing passengers are provided in the next question. The phrase: ”if you also know that” is used, so that the driver would be forced to consider the information from the image before rating the stress level. After the completion of the pilot study, this phrase was characterised as problematic by the trainers (more details in sub-chapter 3.1.6) and replaced by a new one that says: "if, in the previous conditions, you take into account that".

Picture 3

Scenario 28

You are here
Address: Grigoriou Lampraki 69, Pireaus 18534, Attica, Greece

In this street, **the tramway is shared** with **pedestrians**.
The **green arrow** in the picture shows the **direction** of your tram.
There is **no station** in the next 50 m.
There is **no pedestrian crossing** in the next 50 m.
In your road environment, there are **as many pedestrians as** you see in the **image.**

How safe would you feel? Rate from 1 (very unsafe) to 7 (very safe)

Very unsafe (1)	2	3	Neutral (4)	5	6	Very safe (7)
○	○	○	○	○	○	○

If, in the previous conditions, you take into account that:

you are **15 minutes** late compared to the scheduled arrival time to the next station,
all seats are occupied and the number of **standing passengers** is **72** (50% less than the tram standing capacity).

Rate from 1 (not stressful at all) to 7 (very stressful) the level of driving stress, you would feel.

Not stressful at all (1)	2	3	Moderate stress (4)	5	6	Very stressful (7)
○	○	○	○	○	○	○

Figure 5.4: Sample page from the online form

In order to be able to estimate the influence of familiarity on ratings, pictures with similar conditions as scenarios 1, 8, 15, 25, 26 and 36 have been taken in the familiar sections of the network of Athens. The respondent firstly rates the subjective safety of the familiar case and secondly the safety of the unfamiliar case. In the Results chapter, the differences between the two consecutive rates are discussed.

In the penultimate page, the respondent evaluates the importance from 1 (not so important) to 7 (important) of each of the independent variables considered in this study. Furthermore, there are open questions, so that the tram driver can recommend additional factors related with perceived safety and driving stress. In the last one, there are three questions; the first one inquires the gender, the second one the age and last one the experience (personal characteristics).

At this point, it should be noted that a Greek and an English version of the form were developed by the author. In addition, an extra version, which is more suitable for smartphones, was developed per block of question.

5.2.5. Image selection

In Athens, the majority of the images are photographs taken in the field with a smartphone camera. In the first stage, the potential location of each scenario of the table 5.5 was indicated on the online map. The variable values were introduced in the description of each map point.

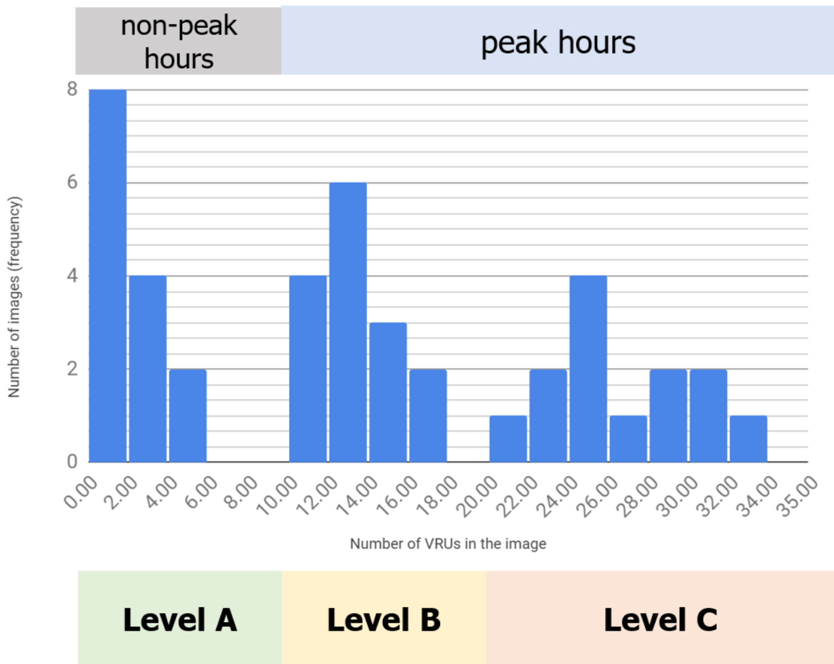

Figure 5.5: Histogram about volume levels of VRUs

The photographs of scenarios, in which the volumes of pedestrians are low (Level A), were taken in the non-peak hours, i.e. at 5:00-7:00 in the morning. Athenians prefer to go shopping in the time period between 11:00-14:00; thus, at this period of the day, the flow of pedestrians at shopping centers, like in Pireaus and Nea Smirni, is quite high. For the stations that are located near the beach, the volume of passengers and pedestrians increases during the summer weekends, when people choose to go swimming or for a coffee by the sea. Lastly, in Neos Kosmos, there is a local street market near the tram track, every Saturday.

In the field, the observer tried to take photographs with many pedestrians (i.e. very crowded case) for Level C scenarios and (almost) without pedestrians for Level A. Level B was selected to be a traffic situation ”located somewhere in between” Level A and Level C. In each spot, many photographs were taken. For each of the developed scenarios, one image was selected, so that the different volume levels can be distinguished clearly by an average respondent. Afterwards, a histogram was plotted in order to determine the threshold value of each volume level. As it can be seen in figure 5.5, the differences in terms of volume of VRUs are clear between each group of pictures.

In each image, the direction of the tram is indicated by a green 3D arrow. Furthermore, through the addition of text to the image, the respondent can be informed about the existence of a pedestrian crossing and a tram stop in the next 50 m. In the end, all the selected images were added both on the online map (given in Appendix B) and the survey form (given in Appendix A).

5.2.6. Pilot study

In June 2019, a pilot study was conducted with the aid of the trainers of the tram drivers in Athens. They were asked to answer the questions of block 1 and write a paragraph with their comments and recommendations. STASY has 4 trainers; all of them are male. They have been working in the tram company since the beginning of its operations in 2004; therefore, all the respondents have 15 years of experience. Their age is between 41 and 50 years.

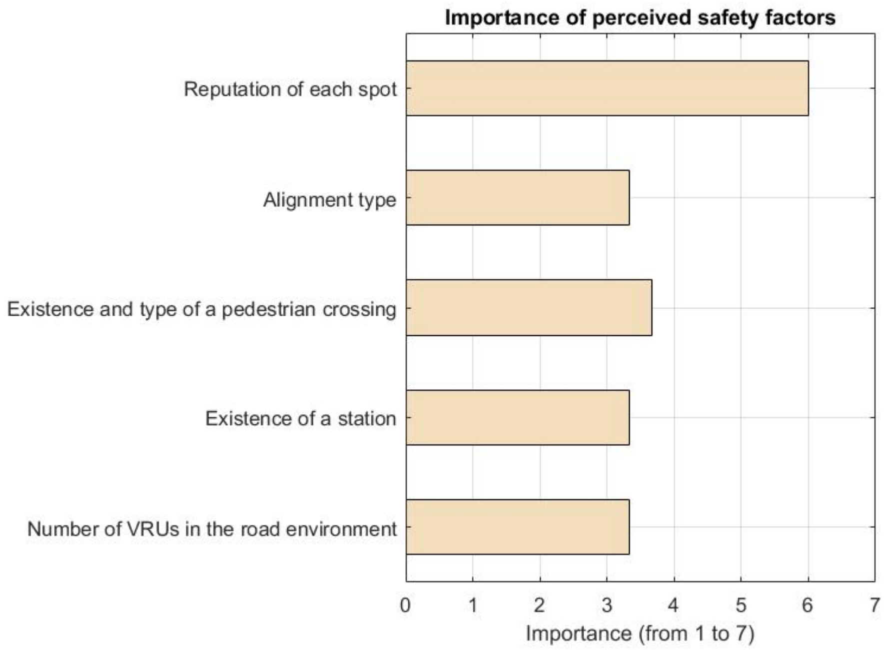

Figure 5.6: Assessment of perceived safety factors (pilot study)

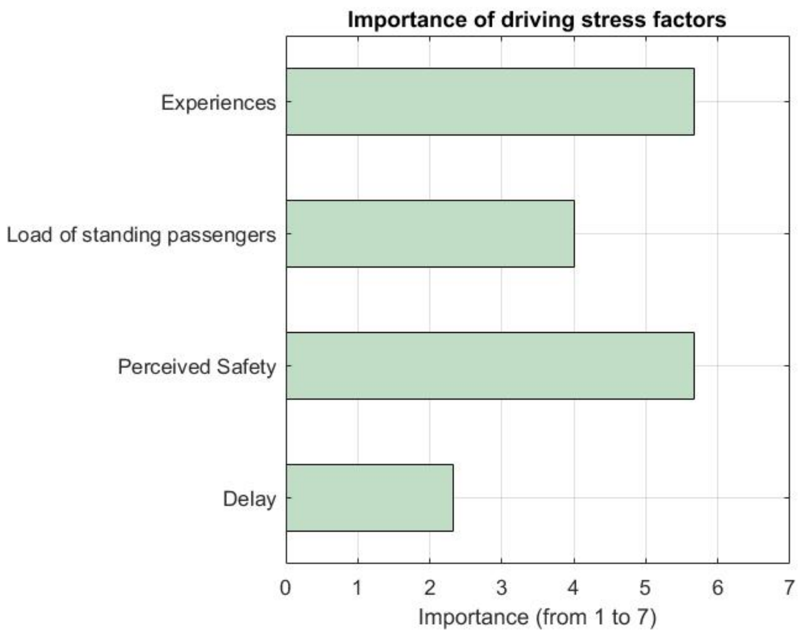

Figure 5.7: Assessment of driving stress factors (pilot study)

In the assessment of factors, trainers selected the reputation of each spot as the most important one. This means that some points of the network have been already characterized as unsafe by the tram drivers based on the occurrence of past severe incidents. Therefore, the perceived safety drops in these sections. The existence and the type of pedestrian crossings comes second with a score of 3.67. A score of 3.33 is observed in the factors related with the number of VRUs in the road environment, the existence of a station and the alignment type. Regarding the stress factors, perceived safety is the most important one, according to the trainers of STASY. The factor of experiences presents almost the same score as the previous factor. The arrival delay has the lowest score, equal to 2.33. Figures 5.6 and 5.7 show the assessment of perceived safety and stress level factors.

As it can been observed in figure 5.8, the existence of a non-exclusive alignment and an increased number of pedestrians results in low perceived safety. In general, trainers preferred to assess safety with grades between 2 to 6 and they tried to avoid extreme values, such very safe (7) and very unsafe (1). In most scenarios of block 1, the mode was equal to 4 (neutral). Furthermore, in cases with VRU volume levels equal to C (see table 5.2), the maximum rate of perceived safety given by the trainers is equal to 4. Regarding the assessment of stress, 2 out of 4 respondents evaluated all the scenarios of block 1 as not stressful at all (1). The scenarios with the maximum delay of 10 minutes and the scenarios with high load of passengers were not evaluated as more stressful compared to the other scenarios. Furthermore, the strong inverse correlation between perceived safety and stress level was not observed.

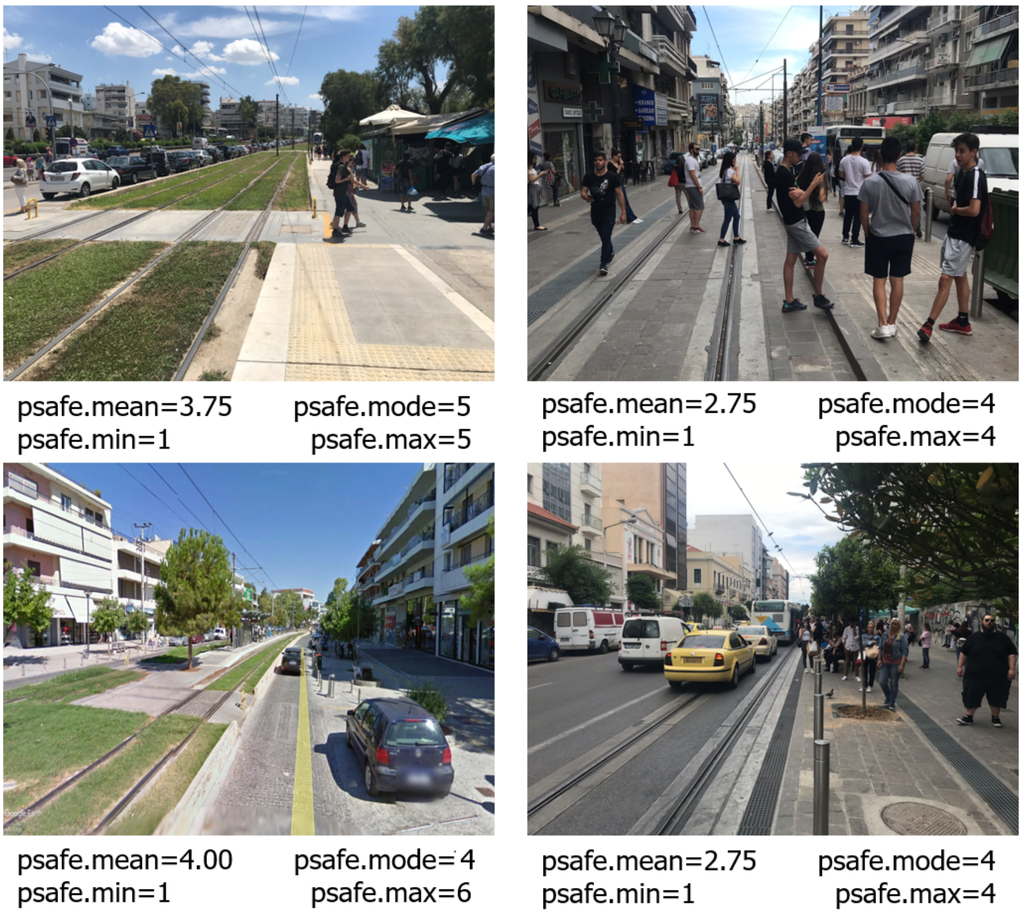

Figure 5.8: Perceived safety levels of different scenarios (pilot study)

With this set of data, first models were created by doing a simple linear regression. The model estimates are shown analytically in the Appendix C. In the perceived safety model, none of the parameters is statistically significant for a confidence interval of 95%. The number of respondents was very limited, but the number of observations was not (56 observations of perceived safety and 48 observations of driving stress). It was concluded that the subjective nature of perceived safety requires a quite higher number of tram drivers and (possibly) the introduction of random effects, so that the heterogeneity in ”tastes” among the individuals can be considered. The sign of the volume of VRUs is negative; thus, more pedestrians in the image result in less safety felt by the trainers of STASY. The existence of an infrastructure shared with pedestrians seem to influence negatively the perceived safety. Positive sign exists only in the parameter of align3. It means that semi-exclusive alignments located near the sidewalk are safer compared to semi-exclusive ones, located (mainly) in the middle of the street. In the model related with the stress levels, all the beta parameters are statistically insignificant. Furthermore, it seems that trainers did not consider the information provided by the picture in the evaluation of driving stress. Perceived safety is more insignificant than the other parameters, while in the assessment of factors, perceived safety was selected as the most important one.

By studying the comments and the recommendations provided by the trainers of STASY, explanations regarding the poor results of the stress model can be given. Trainers stated that it was not clear if the second question about stress was fully connected with the picture at the beginning of each page. Furthermore, the 10 minutes delay usually occur during peak hours in Athens. This delay is taken into account in the schedule design and it does not add extra pressure to the tram drivers. Regarding the description of the load of standing passenger, trainers recommended the use of absolute numbers of standing passengers instead of proportions. The inattention of pedestrians, while crossing the tram line, is the main cause of the recorded accidents between trams and pedestrians occurring in Athens, according to the trainers. Lastly, trainers informed us that tram drivers have not driven in the new section in Piraeus yet; therefore, only trainers have participated in the tests.

The feedback provided by the pilot study was very important in order to update the questionnaire form. It should be acknowledged that neither the author nor the committee has ever driven a tram. Therefore, in this study, there is no personal experience, which will allow the research team to interpret better the challenges of tram drivers, as it happens in studies about car driving behavior. Moreover, the values of delay changed by consulting the managers of STASY. In the low, medium and high scenario, the arrival delay will be equal to 5, 15, 25 minutes respectively (see table 5.2). Regarding the standing passengers, the company informed the author that only one type of trams is used in the operations. Hence, standing capacity is fixed and equal to 143 (4 passengers per square meter). Absolute numbers of standing passengers are added in the form and proportions are now given in parenthesis. As it has been discussed above, the phrase: ”if you also know” was replaced by a new one: ”if, in the previous conditions, you take into account that”, in order to force the respondent to consider the picture in the evaluation of stress level (see figure 5.4). To take into account the influence of familiarity in the analysis, two additional familiar cases with non-exclusive alignment were added in each block of questions. Lastly, no action was taken by the research team regarding the recommended factor related with the inattention of pedestrians, since in a single image, the behavior of pedestrians cannot be observed appropriately.

5.3. Accident data

The objective safety can be analysed either by recorded accidents or by traffic conflicts observed in traffic video recordings. A lot of hours of video from many different locations are required to perform a detailed safety analysis. The author of this thesis did not have access to traffic videos, neither in the Netherlands nor in Greece. There were some privacy issues, which could not be overcome in a 6-month period. Accidents records was the only option for the examination of objective safety.

The Road Safety Observatory of the National Technical University of Athens provided a dataset, that contained tram accidents that have occurred in Athens. Unfortunately, in this dataset, there were only 7 tram-VRU accidents. BRON database, which was developed by the Institute of Road Safety Research (SWOV) and contains the police-reported road accidents that have occurred in the Netherlands, was an important alternative option. From this database, a dataset including the crashes between tram/trains and pedestrians/cyclists/mopeds that have been recorded in the city of Amsterdam in the decade 2007-2017 was downloaded and used in the next step of the analysis. Definitely, it was the most informative dataset that the author of this thesis had access to. Each tram-VRU accident that has occurred in Amsterdam is described by 8 attribute fields, namely: the ID, year, month, time, street name or junction, 1st participant, 2nd participant and accident severity.

In the BRON database, one of the major issues is that the tram accidents are not distinguished from metro or train accidents. The knowledge regarding the location of these events helped the author in order to find the tram crashes. In addition, it was not feasible to include in the dataset accidents, in which the tram was involved as a third party (e.g. pedestrians who run in the street in order to ”catch” the tram in the tram stop). Hence, the dataset contains only primary collisions. It has to be illustrated that some of the incidents have not been registered by the Police, or the consequences of these events have been misreported (SWOV, 2016). For this reason, the opinion of Niels Bos, who is a specialist in accident data analysis and works in SWOV, regarding the quality of the dataset, was asked at the beginning of this process. He stated that not every incident recorded with trams is considered a road traffic accident. Suicides by jumping in front of the rail vehicle and accidents at the maintenance site of the tram company are not included in the BRON database. The completeness of this database regarding fatal accidents is satisfactory (i.e. 90%); but it is less than half-complete regarding the crashes with material damages only. Therefore, the crashes between trams and bicycles/mopeds with material damages only are not studied in this analysis.

The final dataset, which was used in the analysis, contains 122 (sample size) tram accidents that have occurred in Amsterdam in the decade 2007-2017. All of them are mapped in a Geographic Information System (GIS) using the addresses reported by the police. The sample size is relatively small to run a regression analysis and compute crash severity models, as it is happens with perceived safety. Ye and Lord (2014) have estimated that more than 1000, 2000 and 5000 accidents are required in order to compute an ordered probit, multinomial logit (MNL) and mixed logit (ML) model, respectively. For that reason, a simple statistical analysis to uncover some interesting trends related with objective safety of tram lines is preferable.

Tram accidents have to be classified according to the consequences. To make things easier, three categories have been introduced in this analysis, namely: fatal, serious road injuries and minor road injuries. According to SWOV (2017), serious road injuries refer to seriously injured people, who have been subsequently admitted to a hospital with minimum injury AIS value equal to 2. Only casualties that were reported to the police as slight road injuries are classified in the category of minor injuries. Weights, according to the accident severity, were added to the table for each accident. Fatal accidents are equal to 5 Victim Equivalents (VE), accidents with severe injuries are equal to 1 VE and accidents with minor injuries are equal to 0.2 VE (Marti et al., 2016).

By looking into the timetables of GVB (transport operator of Amsterdam), it was obvious that tram operations are more frequent during peak hours, i.e. 6:30-9:00 and 16:00-18:30. An extra field, that shows if one accident has occurred during peak hours, was introduced in the attribute table of accidents.

5.4. Spatial Data

Spatial data is necessary to conduct the analysis of objective safety analysis in Amsterdam and to support the stated preferences experiment in Athens. By using this spatial data, online maps of two study tram networks have been developed and are presented in Appendix B. The links of the online maps are given there, too.

As it is shown in figures 5.1 and 5.2, the tram network of Athens and Amsterdam can firstly be classified according to the alignment type. The alignment types are presented analytically in table 2.1. Google Satelite images and Google StreetView were used in this process. A shapefile with the location of the tram stops in Amsterdam was downloaded from: `www.maps.amsterdam.nl`; in Athens, the tram stops are mapped by the author. The attribute table of the tram stops contains a column that indicates the name of each station.

To design the stated preferences experiment, it is necessary to know the exact location of the new section of the tram network in Athens. As it has been mentioned, the tram drivers have never driven in the new section of Piraeus; therefore, the lack of familiarity is expected to influence the ratings. To collect images with high volumes of pedestrians, it is useful to define attraction poles that exist near the tram lines. The selected attraction points are: Piraeus port, Piraeus city center, Karaiskaki stadium-SEF, SNFCC, Flisvos marina, Alimos beach, Glifada center, Nea Smirni center, Neos Kosmos, Zappeio, Kallimarmaro, National Garden, the Temple of Olympian Zeus and Syntagma. Around these poles, circular buffer zones with different radius (more details in Appendix B) were plotted. It is expected that the flow of pedestrians in the streets, which are inside the buffer zones, is higher at peak hours in comparison with other locations of the network; thus, it is much easier to collect images with Level C volumes. The selection of the location of each scenario is accomplished by considering the collected spatial data of the tram network of Athens and the survey design. In the next stage, the location of each scenario is mapped. Additional pieces of information, such as: scenario number, address and scenario image, are added in the attribute table.

The selected independent variables in the stated preferences survey can be introduced in the spatial analysis of tram accidents, which have occurred in Amsterdam. During the decade 2007-2017, changes in the design of tram lines have been done in Amsterdam; past Google Earth images (i.e. historical imagery tool) were used in order to know the exact design at the time each accident happened. In Amsterdam, all the pedestrian and cycling crossings are mapped in GIS using Google StreetView and the transport map of Openstreetmaps. In the attribute table, details about the level of protection of each pedestrian crossing (e.g. protected and unprotected crossings) can be imported. In this analysis, the cycling intensity of each street of Amsterdam, as it was estimated during the Dutch Bicycle Count Week 2016, can be imported. The flow of pedestrians is expected to be higher in the Centrum (central district of Amsterdam) and around touristic attraction poles that are selected in Amsterdam, namely: Amsterdam Central Station, Westermarkt, Damrak, Dam square, Rokin, Muntplein, Rembrandtplein, Waterlooplein, ARTIS, Leiderstraat, Leidseplein, Vondelpark and Museumplein. By utilizing the geoprocessing tool ”buffer”, circular zones of influence with radius equal to 50, 100 and 150 m are designed in crossing, tram stop and attraction pole locations, respectively. The main idea behind the selection of the previously mentioned radius was to empirically define zones, where the volume of VRUs is increased due to the presence of a crossing, a tram stop or an attraction pole. At this point, it has to be mentioned that surely, there is an uncertainty of more than 50 m in the localization of accidents; buffer zones partly limit this problem.

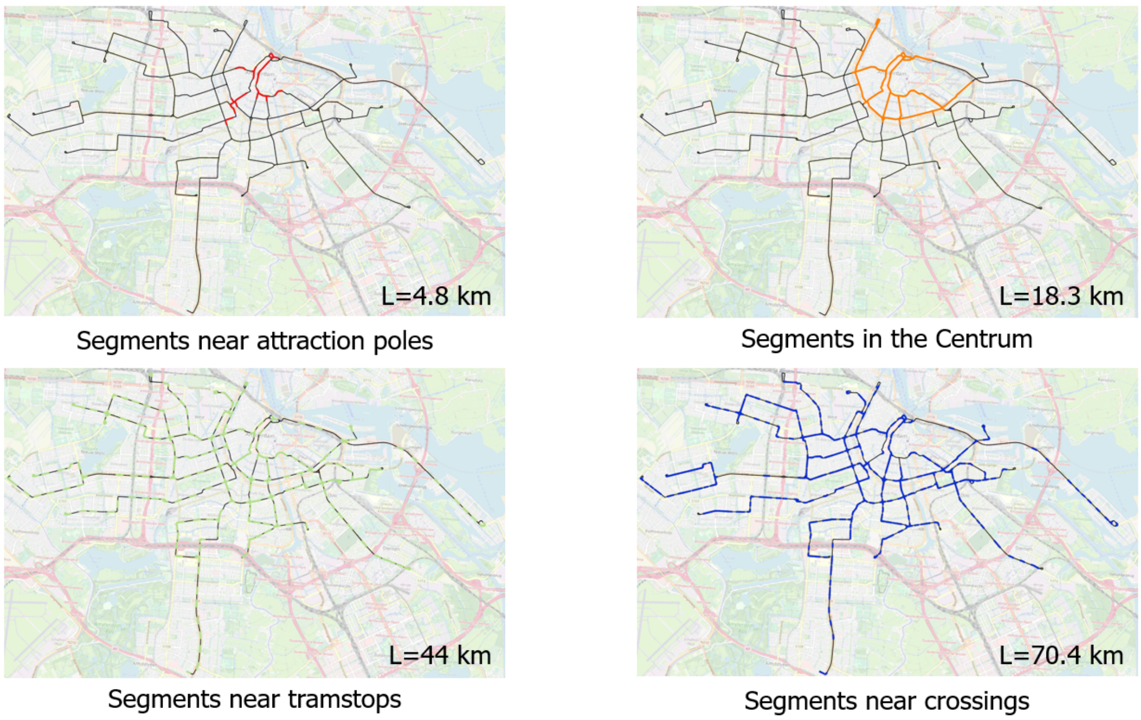

Figure 5.9: Characteristics of the tram network of Amsterdam

An important indicator that has to be computed in the accident analysis is the number of accidents per km. It is a relative indicator and helps one to understand if the accident risk is higher, for example in a semi-exclusive compared to a mixed traffic alignment, or if relatively more crashes appear near unprotected crossings. The total length of the segments per alignment type can be estimated easily in the GIS. In order to compute the total length of segments inside the previously defined buffer zones, the geo-processing tool, called ”intersect”, has to be utilized. The purpose of this algorithm is to extract the overlapping portions of the features by considering the input (i.e. tram network of Amsterdam) and the overlay layer (i.e. the buffer zone of each element). The result of this process is shown in figure 5.9. The total length of segments inside the buffer zones is estimated by adding the lengths of all these overlapping portions. The estimates are also shown in figure 5.9.

5.5. Conclusions

The chance to examine the impact of familiarity in perceived safety and driving was one of the key reasons why the tram network of Athens was selected as study case for the stated preferences experiment. Tram drivers of Athens have never driven in non-exclusive alignments; therefore, their thoughts/feelings about the new section located in Piraeus are reported for the first time. In addition, a first assessment of tram safety in this new section is conducted through the stated preferences experiment. On the contrary, the tram network of Amsterdam has a wide range of different tram alignments. Moreover, the volumes of pedestrians and cyclists in the streets of Amsterdam are among the highest in Europe. Many interactions between VRUs and trams occur every day in the central areas of this city; it is questionable whether the previously mentioned fact results in many severe accidents. In general, observations related with perceived safety and driving stress are collected from the network of Athens and accident records are collected from Amsterdam.

The methodological tool for collecting observations related with perceived safety and driving stress of tram drivers of Athens is an online survey, which was developed in this thesis. This methodological tool, after undergoing some modifications, is also suitable for other tram networks of the world. Dependent variables are: the perceived safety and driving stress and independent variables are: alignment type, existence and type of pedestrian crossings, existence of stations, volume of VRUs, load of standing passengers, arrival delay, familiarity and some personal characteristics, such as: gender, age and experience. By considering the number of levels of each of the previous explanatory variables, a fractional factorial design was developed for this experiment. It contains 36 scenarios (or profiles), which are divided into 3 blocks (12 scenarios per block). For each scenario, two questions were expected to be answered, by giving a rate in a 7-point Likert Scale, namely: (1) how safe you would feel and (2) how stressed you would feel while driving in each section. Images for each of the scenarios were collected from the field. The images were selected, so that the respondent can easily distinguish the different volume levels of pedestrians. A pilot study with the trainers of the tram drivers was conducted in Athens. A problem that was acknowledged was that most of the respondents did not use the pieces of information provided by the images to answer the questions about driving stress. Based on the feedback given by the trainers, some phrases in the online form, as well as some variable values (e.g. arrival delay), were modified.

A dataset, which contains tram-VRU accidents that have occurred in Amsterdam in the decade 2007-2017, was downloaded from the BRON database. This database was developed by the Institute of Road Safety Research (SWOV). The sample size is equal to 122 accidents. It was the only informative dataset the author of this thesis had access to. According to Ye and Lord (2014), it is not feasible to compute accident severity models using a dataset that contains less than 1000 reported crashes. Therefore, only some interesting statistical trends and spatial patterns can be extracted. For each accident record, the ID, the address, the date/time, the type of participants and the accident severity are known. Three severity levels are observed in the used dataset, namely: fatal accidents, accidents with severe road injuries and accidents with minor injuries. The crashes between tram and bicycles/mopeds were removed from the analysis. Dr. Niels Bos from SWOV informed the author that the BRON database is less than half-complete regarding the crashes with material damages, while the completeness regarding the fatal tram crashes is higher than 90%.

Spatial data points are necessary to analyse the objective tram safety in Amsterdam. In addition, they have contributed to the design of the stated preferences experiment, which is conducted in Athens. The majority of spatial data points was collected by looking at Satelite images of Google Earth, Google StreetView images and transport maps of Openstreetmaps. The categorization of the tram networks according to the level of separation from the other road users helped the author in order to determine the location of the scenarios in the beginning of this process. Furthermore, the identification of the attraction poles near the tram network of Athens was of key importance in order to collect images from the field with high levels of VRUs (e.g. Level C). In Amsterdam, vector data (i.e. ESRI shapefiles) related with the tram network and the tram stops was downloaded from `www.maps.amsterdam.nl`. The pedestrian crossings were mapped by the author and the level of protection was imported in the attribute table of this vector layer. In order to define the points where VRUs are more exposed to tram accidents, the locations of attraction poles were indicated, the cycling intensities (as they were measured in the Dutch Bicylcle Count Week) in the cycle links of Amsterdam were added and the tram sections that are located inside the city center of Amsterdam were selected in the developed GIS.

6
Results

The objective of this chapter is to present the results obtained from the stated preferences survey conducted in Athens and the objective safety analysis conducted in Amsterdam. The results refer to three perspectives of tram safety, namely perceived safety, driving stress and objective safety. Proportional odds method is used in the development of perceived safety and driving stress models. The responses from the stated preferences survey is main input in the models estimation process. Black spot analysis is conducted for determining the spatial patterns of tram accidents. Also, some interesting statistics related with tram accidents are presented in this chapter.

6.1. Perceived safety

For the identification of the factors that influence perceived safety in tram tracks, a stated preferences survey was conducted with the aid of tram drivers of the network of Athens. The survey form was available on the internet from 11 July to 29 July 2019 (i.e. 18 days). Respondents could answer the questions of the survey by using either a computer or via smartphone/tablet. The managers of STASY distributed the links to the tram drivers and they mailed them weekly notifications to complete the survey. Drivers were divided alphabetically into 3 groups, i.e. one group per block. Each respondent could answer only one block of questions by one IP address.

6.1.1. Sample characteristics

The developed form was answered by 57 out of 118 tram drivers (48%), who are working in STASY right now. There were 7 respondents who did not answer all the questions of the survey. Also, 2 full responses from the total 50 were discarded, so that the number of responses in each block will be the same and equal to 16. These responses had the lowest variability in the given grades. Same number of observations in each block means no correlations among the independent variables and consequently, more statistically significant beta parameters. Every respondent rated the perceived safety 14 times (i.e. 14 different scenarios per block). According to the statistics provided by the online survey platform, the average time to complete the survey was equal to 18.1 minutes, despite the fact that the survey was expected to be completed in 10 minutes. Lastly, it was observed that the majority of the tram drivers answered the survey via smartphone or tablet, i.e. 40 of the total 57 drivers (70%).

In the questions related with demographics, there was an option for those that were not interested to inform the research team about their gender, age and experience. This option was given in order to ensure the anonymity of the tram drivers as much as possible. Eleven drivers preferred not to inform the research team about their age. From the rest 37 drivers, 33 (89%) of them were males and only 4 (11%) were females. Today, only 9 female drivers (7.6%) are working in STASY. The questions about the age were answered by 36 drivers. The majority of them, i.e. around 60% of the respondents, belonged to the age-group of 41-50 years. Today, the mean age of the STASY drivers is equal to 42 years. Most of the respondents, i.e. 30 out of the 37 drivers, who answered the question regarding their experience, have been in the tram company since the beginning of its operations in 2004. Generally speaking, the average experience of the tram drivers of Athens, is almost 13 years. At this point, it should be mentioned that only 32 drivers answered all the questions related with the demographic characteristics (i.e. gender + age + experience). The missing responses and the low variance in personal characteristics makes the introduction of relevant beta parameters unfeasible in the estimated models, as it is explained in Appendix C. Yet, by observing the numbers and the proportions, it can be said with certainty that the sample is representative for the examination of perceived safety and driving stress.

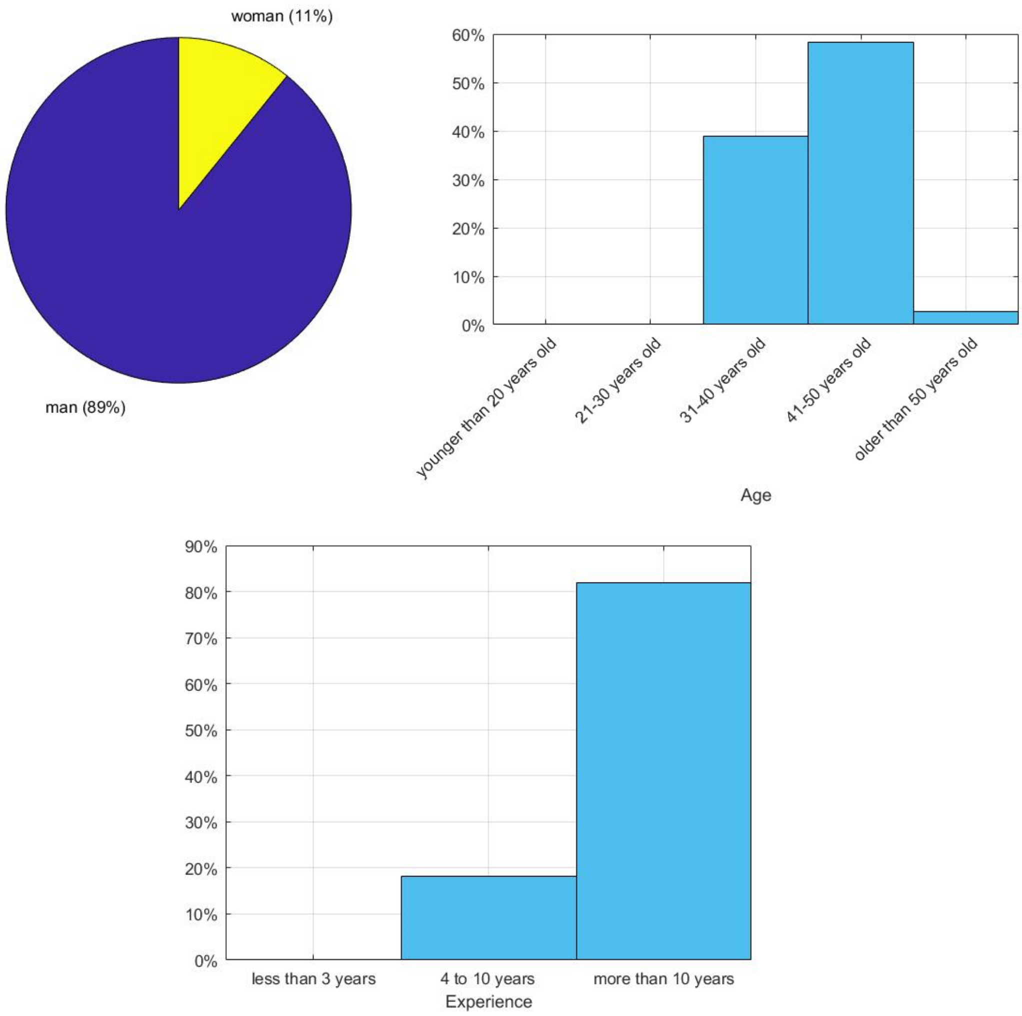

Figure 6.1: Sample characteristics

6.1.2. Assessment of factors

Before answering the questions about their personal characteristics, respondents assessed the importance of perceived safety factors, as it has been presented in table 5.2 in the previous chapter. The alignment type and more specifically the level of separation from the motorized and non-motorized traffic was selected as the most important parameter with a mean grade of 5.7/7. In the second place with a mean score of 5.5/7 is the factor related with the number of VRUs in the road environment. The mean grade of factors connected with the reputation and the existence of a pedestrian crossing is 5.5 and 5.4/7 respectively. In all the previously mentioned parameters, the mode score is equal to 7/7. The existence of a station was characterized by the tram drivers as an unimportant factor, with a mean score equal to 3.3/7 and the mode score equal to 1/7. Lastly, in all factors of perceived safety, the minimum and maximum grades given by the respondents were equal to 1 and 7, respectively.

In the next step, respondents recommended one more perceived safety factor, which is not considered in this analysis and is important, according to their views. Visibility problems were illustrated by 9 out of 50 drivers. Some of them were more specific in their description; they pointed out locations in the network with sharp curves and trees. Factors related with the behavior of pedestrians, such as: lack of situational awareness, unpredictable behavior and violation of rules, were recommended by 6, 5 and 5/50 respondents, respectively. These results are in line with the key challenges of tram drivers (figure 2.5) as they are presented by Naznin et al. (2017). Two drivers posed extra issue, that of functionality of traffic lights. Other recommended factors are slope existence, fatigue, u-turns made by cars and stress of the other road users.

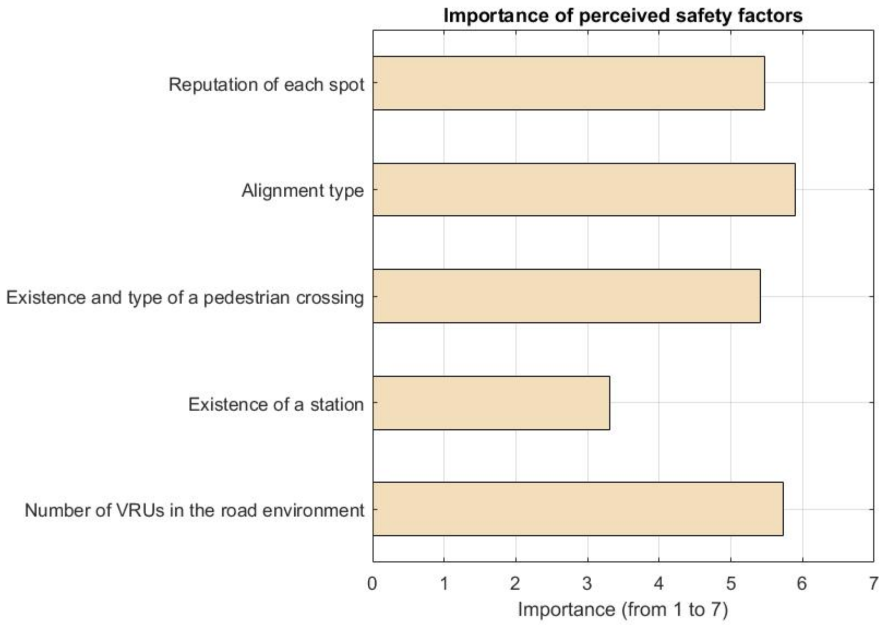

Figure 6.2: Assessment of perceived safety factors

6.1.3. Contribution of familiarity

As it has been mentioned, tram drivers rated perceived safety twice in two out of 12 scenarios contained in each block. At the top of the page, there was a photograph from a section located in the present network (with familiarity) and in the next question, there was a photograph from a new section in Piraeus (without familiarity). Apart from familiarity, the driving conditions were very similar; therefore, the differences between two consecutive ratings describes the contribution of familiarity to perceived safety. Every block had two pairs of scenarios; therefore, 16 differences (i.e. 16 respondents per block) were recorded for each of the total 6 pairs (i.e. 2 pairs per block).

Mean	-0.5625
Mode	0.0000
Standard error	0.1155
Median	0.0000
Standard deviation	1.1315
Sample variance	1.2803
Minimum	-4
Maximum	3
Range	7
Count	96

Table 6.1: Descriptive statistics of perceived safety differences due to unfamiliarity

The mean difference between these two consecutive ratings of perceived safety is computed equal to -0.562. The negative sign illustrates that the scenario with familiarity was considered as safer compared to the scenario without familiarity. The mode difference is equal to 0 and its minimum and maximum values are estimated equal to -4 and 3 respectively. The highest mean difference (-1.4375) is observed in the pair of scenarios 26-126 and the lowest (-0.250) in the pair 15-115. Scenario 25 (without familiarity) was assessed as safer (+0.313) compared to scenario 125 (with familiarity). The changes of perceived safety ratings of the rest three pairs, namely: 1-101, 8-108 and 36-136, are equal to -0.625 and -0.6875, respectively.

At this point, it has to be acknowledged that scenario 125 is located next to a present tram stop, where the highest passenger traffic is reported today. In this location, the passengers cross the tram line, right after disembarking, in order to transfer to the metro station of Neos Kosmos; therefore, it is considered by the drivers as a quite unsafe spot. In addition, sections around Plateia Deligianni and Agia Triada tram stops (scenario 1, 8, 26 and 36) in the new section of Piraeus already have a poor reputation among the tram drivers. Generally speaking, high decreases or increases of perceived safety, solely because of familiarity, have not been observed in this analysis. All of the previously mentioned differences can be described appropriately by the subjective nature of perceived safety. The subjectivity is considered in the model estimation performed in the next step.

6.1.4. Ordinal regression model

Ordered logit (or proportional odds method) with random effects was used for the computation of perceived safety models. The proportional odds assumption was tested by performing a X^2 test; for only a 70% confidence interval, the model without the proportional odds assumption represents better the population. The output from this test and the full story behind the computation of perceived safety models are presented in the Appendix C.

The estimation of ordered logit models with random effects is achieved through the Simulated Maximum Likelihood (SML) method (see equation 4.11). All the beta parameters are selected to be random. In order to obtain statistically significant results for a 95% confidence interval, the simulations were based on 2000 Halton draws. In addition, in some of the models, such as the ones presented in this sub-chapter (more models in the Appendix C), the number of "observations" contained in the dataset was reduced to 576 (i.e. $12 * 48 = 576$ observations), in order to eliminate the correlations between the independent variables.

The estimates, the standard errors and other statistical indicators of the first model of perceived safety are shown in table 6.2. As it can be seen, the parameters "sts" and "align3" are statistically insignificant for 95% confidence interval. In other words, the existence of a station in an image did not influence the rating process. Also, it is proved that there is no statistically significant difference for a 95% confidence interval between a semi-exclusive alignment near the sidewalk and a semi-exclusive alignment located in the middle of the street. The standard deviations of the other parameters are statistically significant for a 95% confidence interval. Therefore, the alignment type, the existence of protected or unprotected pedestrian crossing and the number of vulnerable road users were correctly selected to be random. All the mean values of the random parameters have negative signs. Hence, a semi-exclusive alignment, located in the middle of the street with protected pedestrian crossings and without people who are walking inside the road environment of the tram driver, is the safest case, according to the estimated model.

The next step is to discard the statistically insignificant parameters and to re-compute the model in order to estimate the final one. As it can be seen in table 6.3, all the mean beta parameters and the standard deviations are statistically significant for a confidence interval of 95%. By using the estimated parameters and the variable values of each scenario, the mean perceived safety and the maximum-minimum perceived safety levels for a confidence interval of 95% can now be estimated. The scenarios: 2, 5, 9, 12, 23 and 34 have the highest level of perceived safety, equal to 5/7 and the scenarios: 3, 6, 7, 10, 26, 28 and 35 have the lowest level, equal to 2/7. If all the variable values of the model were zero, then the perceived safety would be equal to 6/7. It is the maximum safety level according to this model. The model function reaches the minimum value when the number of pedestrians in the road environment tends to infinity. By observing the kappa thresholds (with asterisk) of table 6.3, it is obvious that the interval size (i.e. threshold difference) of neutral (4) level is bigger compared to the other intervals. That is why subjective safety in the majority of scenarios is equal to neutral (4). The biggest difference between the average rating and the model predictions is observed in the second safety level. According to the model estimates, more scenarios are classified in level 2 and not in level 3, as it happens in the case of average ratings. It was observed that there are many scenarios with average values between 2.5-3.

	Estimate	Std. Error	P(>|z|)	Odds ratio
constant	7.647	0.546	0.000	
kappa.1	2.249	0.251	0.000	
kappa.2	3.711	0.307	0.000	
kappa.3	5.863	0.391	0.000	
kappa.4	7.172	0.444	0.000	
kappa.5	8.598	0.507	0.000	
mean.align1	-1.708	0.301	0.000	5.518
mean.align2	-1.517	0.284	0.000	4.561
mean.align3	-0.418	0.279	0.134	1.518
mean.pcrs1	-0.744	0.276	0.007	2.105
mean.pcrs2	-1.685	0.337	0.000	5.392
mean.sts	-0.272	0.204	0.182	1.313
mean.vru_num	-0.139	0.017	0.000	1.149
sd.align1	0.845	0.334	0.011	
sd.align2	0.828	0.314	0.008	
sd.align3	0.820	0.293	0.005	
sd.pcrs1	1.290	0.249	0.000	
sd.pcrs2	1.660	0.283	0.000	
sd.sts	0.510	0.444	0.251	
sd.vru_num	0.088	0.014	0.000	
kappa.0*	-7.647			
kappa.1*	-5.398			
kappa.2*	-3.936			
kappa.3*	-1.785			
kappa.4*	-0.475			
kappa.5*	0.951			
Log likelihood at convergence	-904.2			
Number of observations	576			
Number of iterations	79			
Halton draws	2000			

*Thresholds, as they are estimated by discarding the constant from the final model

Table 6.2: Primary perceived safety model

	Estimate	Std. Error	P(>|z|)	Odds ratio
constant	7.284	0.449	0.000	
kappa.1	2.182	0.234	0.000	
kappa.2	3.593	0.276	0.000	
kappa.3	5.643	0.336	0.000	
kappa.4	6.889	0.374	0.000	
kappa.5	8.253	0.422	0.000	
mean.align1	-1.407	0.249	0.000	4.086
mean.align2	-1.300	0.230	0.000	3.668
mean.pcrs1	-0.840	0.270	0.002	2.316
mean.pcrs2	-1.594	0.306	0.000	4.925
mean.vru_num	-0.131	0.016	0.000	1.139
sd.align1	0.792	0.292	0.007	
sd.align2	0.647	0.000	0.020	
sd.pcrs1	1.231	0.236	0.000	
sd.pcrs2	1.543	0.248	0.000	
sd.vru_num	0.081	0.011	0.000	
kappa.0*	-7.284			
kappa.1*	-5.465			
kappa.2*	-4.054			
kappa.3*	-2.004			
kappa.4*	-0.758			
kappa.5*	0.606			
Log likelihood at convergence	-907.2			
Number of observations	576			
Number of iterations	112			
Halton draws	2000			

*Thresholds, as they are estimated by discarding the constant from the final model

Table 6.3: Final perceived safety model

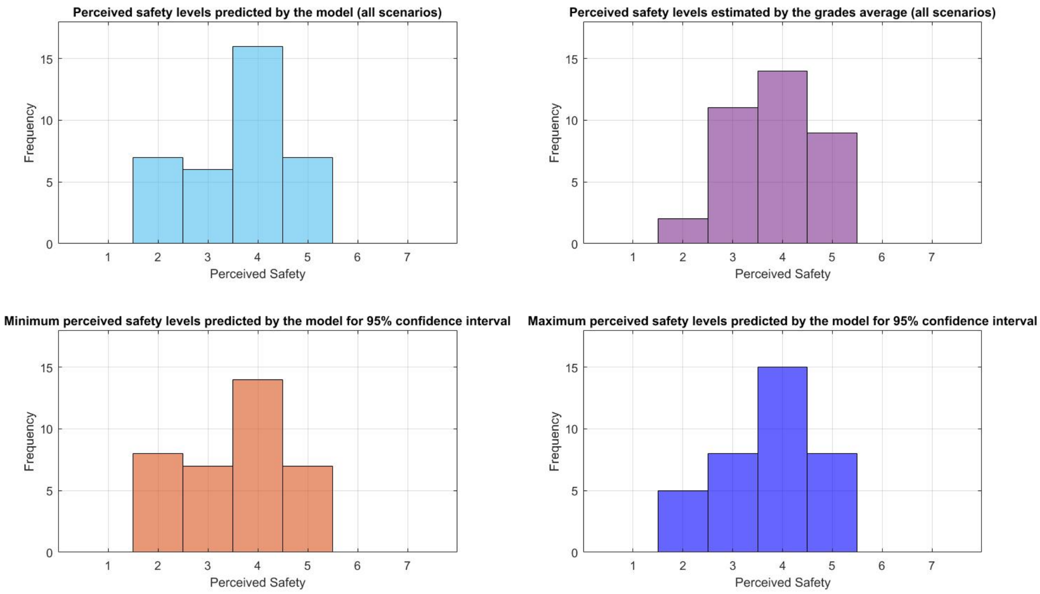

Figure 6.3: Histograms about perceived safety

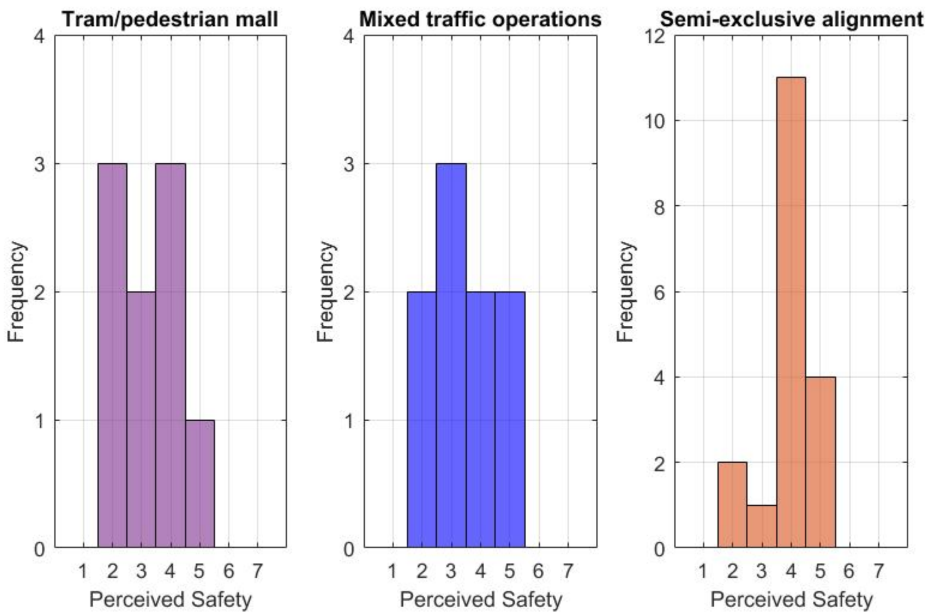

Figure 6.4: The influence of alignment type on perceived safety

According to the estimated model, the tramways that are shared with pedestrians are considered by drivers as the most dangerous ones, compared to the other tram alignments. In addition, it is observed that there is no great difference in perceived safety levels between a mixed traffic operation alignment and a tram/pedestrian mall. Sections with unprotected pedestrian crossings are more unsafe than sections without crossings, according to the views of the respondents. An increased number of VRUs (crowded case) affects more significantly perceived safety compared to the all the other parameters. Indeed, a driving scenario with 30 VRUs in the road environment is 20% more likely to report level 2/7 perceived safety and 30% less likely to report level 6/7, according to the estimated marginal effects that are shown in table 6.4. Regarding the odds ratios, parameters such as: pcrs2 and align1 reported the highest ones, namely: 4.925 and 4.0845, respectively. It means that the existence of an unprotected crossing in one section changes the odds of being in one category less by a factor higher than the ones of the other parameters. The histogram of figure 6.4 proves that a comparatively big number of sections in which the tramway is shared with pedestrians is classified by the estimated model into the second safety level, while many sections with semi-exclusive alignment are classified into higher safety levels, such as level 4/7 and 5/7. Furthermore, scenarios with 10 or less pedestrians are characterized as safer in comparison with more crowded cases.

	Very Unsafe (1)	2	3	Neutral (4)	5	6	Very safe (7)
Tram/pedestrian mall	0.002	0.016	0.050	0.211	0.051	-0.141	-0.190
Mixed operation	0.002	0.014	0.044	0.194	0.056	-0.128	-0.181
Without crossing	0.001	0.007	0.022	0.117	0.059	-0.073	-0.134
With unprotected crossing	0.003	0.020	0.062	0.241	0.040	-0.162	-0.204
Increase of 5 VRUs	0.001	0.005	0.016	0.088	0.053	-0.051	-0.051
Increase of 15 VRUs	0.004	0.031	0.091	0.290	0.008	-0.200	-0.224
Increase of 30 VRUs	0.033	0.195	0.304	0.213	-0.176	-0.301	-0.268

Table 6.4: Marginal effects of perceived safety model

The heterogeneity in ”tastes” can be described by plotting the normal distributions of the random parameters. In figure 6.5, it is obvious that parameters related with the existence and the type of a pedestrian crossing have higher heterogeneity among the individuals. It means that for some tram drivers, the existence of an unprotected crossing is very important in the assessment of safety, while some other drivers do not perceive it as equally important. The heterogeneity of the ”taste” related with the existence of a mixed traffic operation alignment is bigger compared to the ”taste” related with the existence of a tramway shared with pedestrians. The majority of the drivers agree that high volumes of pedestrians in the road environment negatively affect perceived safety.

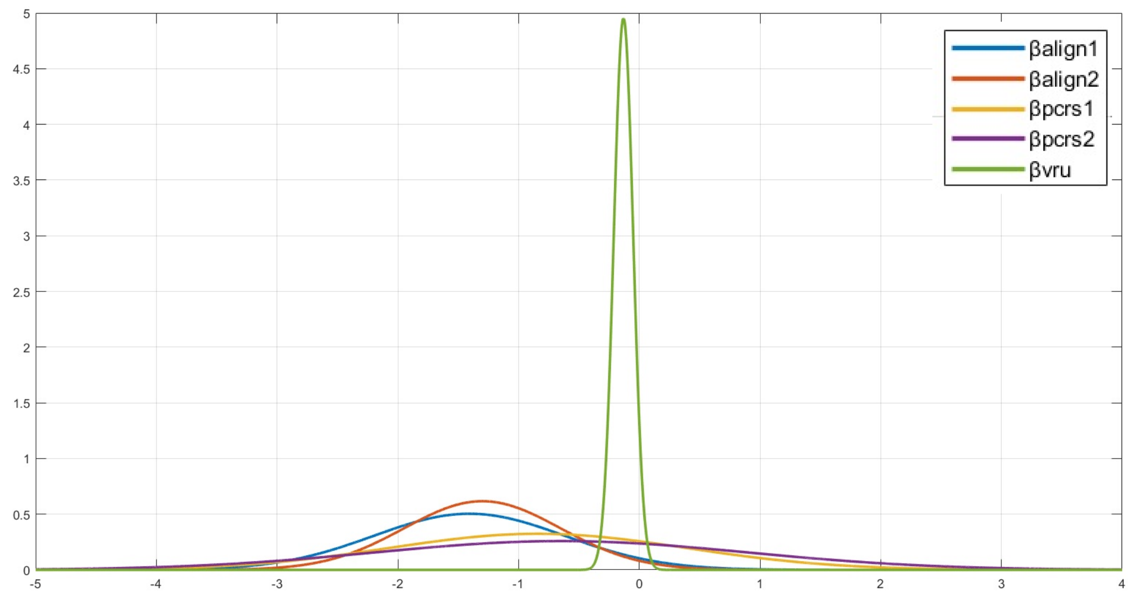

Figure 6.5: Normal distributions of the random beta parameters of perceived safety model

6.2. Driving stress

As it has been mentioned in the methodology chapter, each page of the questionnaire survey contained an extra question related with driving stress (see figure 5.4). Therefore, the sample of the tram drivers is the same as before in the perceived safety analysis, i.e. 48 tram drivers from STASY (i.e. the tram company of Athens) divided into 3 blocks of questions. The 48 tram drivers rated driving stress in 12 scenarios, which were included in each block of questions.

6.2.1. Assessment of factors

Tram drivers rated the importance of driving stress factors that were introduced in the survey. According to their opinion, perceived safety is the most important one, with a score 5.9/7. Negative or positive memories affect their choices, since the experiences factor score was 0.2 smaller in comparison with that of perceived safety. The load of standing passengers and arrival delay do not have the same importance compared to the other two factors. Their mean scores are equal to 4.225 and 4.075, respectively. Figure 6.6 shows the means given by the tram drivers of Athens graphically.

By checking more precisely the descriptive statistics, it is observed that the mode grade (in terms of importance) of the factors related with arrival delay and load of standing passengers is equal to 5/7, while perceived safety has a mode score equal to 6/7. The minimum grade regarding the importance of the perceived safety factor is 4/7. All the other factors of driving stress have minimums equal to 1 and maximums equal to 7. Higher variances of scores about the importance of parameters were observed especially in the factors related with the load of standing passengers and arrival delay. On the contrary, all tram drivers of Athens agree that subjective safety is an important factor that affects driving stress; its variance is the lowest (i.e. 0.974). Hence, tram drivers care more about safety than system efficiency, while they are driving in the tram network of Athens.

Figure 6.6: Assessment of driving stress factors

6.2.2. Ordinal regression model

One of the major problems that was observed in the development of the stress level models was the statistical insignificance of the beta perceived safety parameters (see Appendix C). Perceived safety does not actually correlate with driving stress in all the estimated models. A different approach was to introduce the subjective safety scores, as it was given by each individual in each scenario. In this way, an inverse significant relationship between safety and stress was found. Yet, after the introduction of random effects in the model estimation, this relationship was no longer statistically significant, for a 95% confidence interval. So, in order to compute a model that fits better with the observations, the parameter of perceived safety was replaced by familiarity. Until now, tram drivers have not driven in Piraeus; thus, they do not have experience in driving in tramways that are shared either with pedestrians or with motorized traffic. As it has been mentioned before, the existence of these type of alignments impacts perceived safety.

The estimated model using the method of ordinal regression with proportional odds assumption is shown in table 6.5. The proportional odds assumption was tested by performing a X^2 test; for a 85% confidence interval, the driving stress model without the proportional odds assumption represents better the population (more details in Appendix C). In the estimated model, familiarity is statistically

	Estimate	Std. Error	P(>|z|)	Odds ratio
constant	1.748	0.242	0.000	
kappa.1	1.390	0.155	0.000	
kappa.2	2.441	0.184	0.000	
kappa.3	3.962	0.221	0.000	
kappa.4	5.701	0.276	0.000	
kappa.5	6.928	0.325	0.000	
fam	-1.407	0.167	0.017	4.086
mean.time	-1.300	0.021	0.000	3.668
mean.load	-0.840	0.315	0.007	2.316
sd.time	0.792	0.016	0.000	
sd.load	0.647	0.329	0.020	
kappa.0*	-1.748			
kappa.1*	-6.257			
kappa.2*	-5.206			
kappa.3*	-3.685			
kappa.4*	-1.946			
kappa.5*	-0.719			
Log likelihood at convergence	-922.4			
Number of observations	576			
Number of iterations	59			
Halton draws	1000			

*Thresholds, as they are estimated by discarding the constant from the final model

Table 6.5: Final driving stress model

significant, for a 95% confidence interval (see table 6.5). The standard deviation of this beta parameter was proved statistically insignificant for the same confidence interval; therefore, familiarity is not a random parameter. Random beta parameters of the model are the arrival delay and the load of standing passengers. Their means have a positive sign, while the coefficient connected with familiarity has a negative one. It means that a familiar section decreases stress levels and high arrival delays cause increase driving stress.

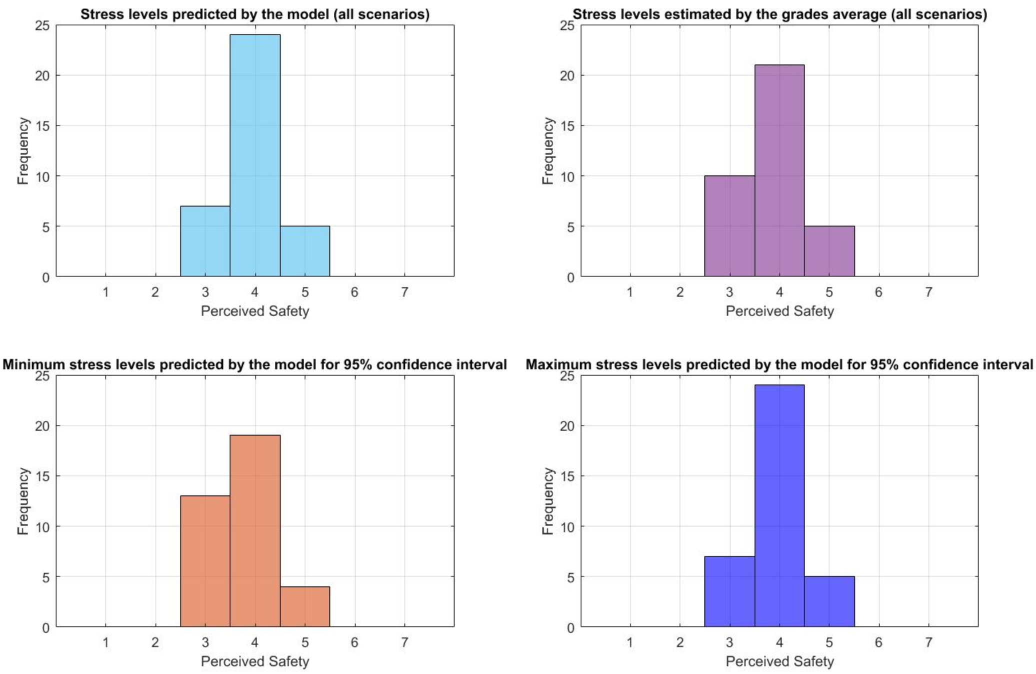

Figure 6.7: Histograms about driving stress

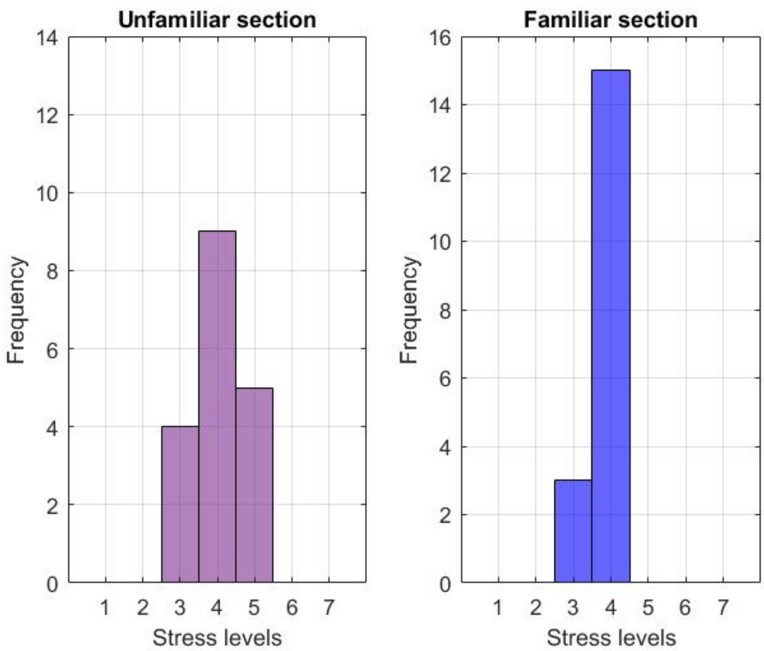

Figure 6.8: The influence of familiarity on driving stress

Driving stress is a more subjective notion compared to perceived safety. In 26 out of 36 scenarios, the range of the given grades was equal to 6 (i.e. the maximum range for a 7-point Likert scale), while in the perceived safety grades, only 6 (out of 36) scenarios exist a range higher than 5. In the end, the average estimates of driving stress converge to the more moderate levels. Indeed, the minimum value of the means is equal to 2.62 and the maximum is equal to 5.37. As it can be seen in the kappa thresholds (given with asterisk) of the model, the sizes of the intervals related with the 4th and 5th level of driving stress are much bigger compared to the other intervals. According to the estimated model (considering the means of the random beta parameters), if arrival delay is zero, the proportion of standing passengers is less than 50% and the route is familiar to the tram drivers, the driving stress is 2/7. On the other hand, if arrival delay is higher than 40 minutes and the number of standing passengers is equal to the tram standing capacity, the model predicts a quite high driving stress level, equal to 6/7.

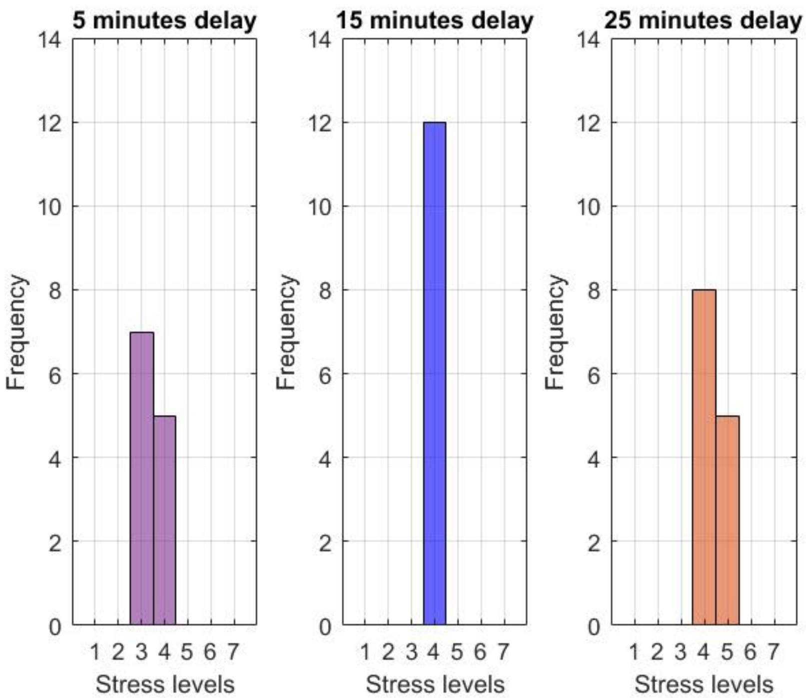

Figure 6.9: The influence of arrival delay on driving stress

	Not stressful at all (1)	2	3	Neutral (4)	5	6	Very stressful (7)
With 5 min delay	-0.044	-0.049	-0.002	0.051	0.034	0.006	0.003
With 15 min delay	-0.099	-0.140	-0.054	0.119	0.132	0.029	0.013
With 25 min delay	-0.126	-0.200	-0.130	0.099	0.250	0.072	0.035
With 50% standing passengers	-0.046	-0.051	-0.002	0.054	0.036	0.007	0.003
With 100% standing passengers	-0.079	-0.102	-0.024	0.097	0.083	0.017	0.007
Familiar section	0.058	0.041	-0.017	-0.051	-0.025	-0.004	-0.002

Table 6.6: Marginal effects of driving stress model

The highest odds ratio equal to 1.483 is observed in the familiarity parameter. The factor of arrival delay has a smaller odds ratio, equal to 0.923. This value means that for 1 minute increase in arrival delay, the odds of being in one category lower change by 0.923. The load of standing passengers does not affect driving stress too much. Indeed, for a tram that is full of passengers, the stress of the tram driver is 8.3% more likely to reach level 6/7. For a 25-minute delay, this chance is equal to 25%. In the table 6.6 that shows the marginal effects, it can also be seen that driving stress in familiar sections is less likely to reach moderate to high stress levels. According to the model predictions, none of the scenarios that were located in the present tram network of Athens reported stress levels higher than or equal to 5/7 (see figure 6.8).

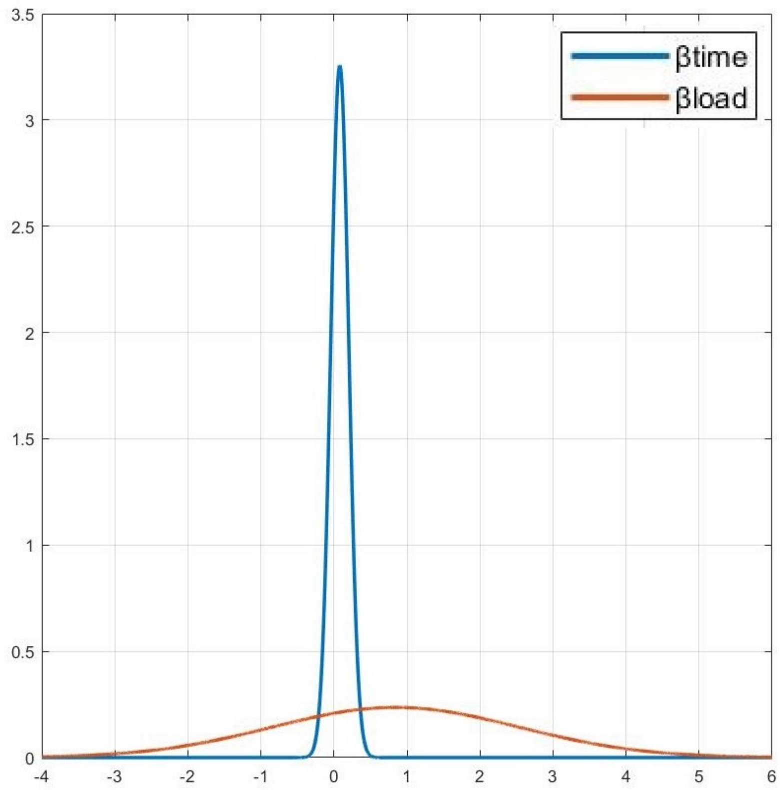

Figure 6.10: Normal distributions of the random beta parameters of driving stress model

The beta parameter related with the load of standing passengers presents higher heterogeneity compared to the beta parameter related with arrival delay. Tram drivers seem to agree that high delays mean high driving stress. In addition, they totally agree about the contribution of familiarity to driving stress. For this reason, the standard deviation of familiarity was proved statistically insignificant for a 95% confidence interval.

6.3. Objective safety

As it has been mentioned, the analysis of objective safety of tram lines was accomplished in the tram network of Amsterdam utilizing a dataset, which was downloaded from the BRON Database. It was the most comprehensive dataset that the author of this thesis had access to. This dataset contained 122 accidents observed in the tram network of Amsterdam between trams and VRUs (mopeds were included too) in the decade 2007-2017. Their location was mapped in a GIS in order to extract statistics and spatial patterns relevant to objective safety.

6.3.1. Statistics

The small sample of 122 accidents indicates that accidents between trams and VRUs rarely occur in Amsterdam, which has the highest flows of pedestrians compared to all the other cities of the Netherlands. This conclusion is in line with the observations of previous studies, such as: SWOV (2011) and Marti et al. (2016). In the same period, in the same city, the crashes with injuries between cars and VRUs were 3651, according to the accident data of BRON Database. Each year, around 11.09 tram-VRU crashes were recorded. In the majority of these events (i.e. 78.69%), pedestrians, cyclists, or riders of mopeds were seriously injured. The indicator of fatal accidents per year was estimated equal to 1. The correspondent rate of crashes with minor injuries is higher by 0.36.

	Total	Fatal		Severe injury(ies)		Minor injury(ies)	
		Total	Share	Total	Share	Total	Share
Bicycle	**47**	3	6.38%	37	78.72%	7	14.89%
Moped/Light moped/Three-wheels scooter	**18**	1	5.56%	13	72.22%	4	22.22%
Pedestrian	**57**	7	12.28%	46	80.70%	4	7.02%
Total accidents (2007-2017)	**122**	11	9.02%	96	78.69%	15	12.30%
Accidents per year	**11.09**	1.00		8.73		1.36	

Table 6.7: General characteristics of the accidents dataset

Compared to all the other groups of VRUs, pedestrians are surely more vulnerable. Indeed, in 7 out of 11 fatal accidents, there was the involvement of a pedestrian (see table 6.7. In addition, the group of pedestrians has the lowest share of accidents with minor injury(ies). On the contrary, the share of accidents between mopeds and trams is the smallest compared to that of all the other modes. In the 22.22% of the reported crashes that occurred in Amsterdam, the rider of the moped was slightly injured. The number of incidents between tram and cyclists is lower by 10 compared to the correspondent number between trams and pedestrians. In the study decade, three cyclists died from a collision with tram.

		Total accidents (2007-2017)	Fatal		Severe injury(ies)		Minor injury(ies)	
			Total	Share	Total	Share	Total	Share
Alignment Type	Exclusive	**1**	0	0.00%	1	100.00%	0	0.00%
	Semi-exclusive	**29**	7	24.14%	20	68.97%	2	6.90%
	Mixed traffic operations	**82**	4	4.88%	66	80.49%	12	14.63%
	Tram/pedestrian mall	**10**	0	0.00%	9	90.00%	1	10.00%
Tramstop	With tramstop in the next 100 m	**65**	7	10.77%	49	75.38%	9	13.85%
	Without tramstop in the next 100 m	**57**	4	7.02%	47	82.46%	6	10.53%
Pedestrrian /cycling crossing	Without crossing in the next 50 m	**32**	2	6.25%	25	78.13%	5	15.63%
	With unprotected crossing in the next 50 m	**22**	3	13.64%	17	77.27%	2	9.09%
	With protected crossing in the next 50 m	**68**	6	8.82%	54	79.41%	8	11.76%
Cycling intensity	Level A (<20 cyclists)	**5**	2	40.00%	3	60.00%	0	0.00%
	Level B (20-100 cyclists)	**20**	2	10.00%	16	80.00%	2	10.00%
	Level C (100-500 cyclists)	**71**	4	5.63%	59	83.10%	8	11.27%
	Level D (>500 cyclists)	**26**	3	11.54%	18	69.23%	5	19.23%
Attraction pole	Next to an attraction pole (buffer zone radius = 150 m)	**33**	2	6.06%	27	81.82%	4	12.12%
	Away from an attraction pole (buffer zone radius = 150 m)	**89**	9	10.11%	69	77.53%	11	12.36%
Districts	In the Centrum	**36**	0	0.00%	29	80.56%	7	19.44%
	Outside of the Centrum	**86**	11	12.79%	67	77.91%	8	9.30%
Time	At peak hours (6:30-9:00, 16:00-18:30)	**37**	3	8.11%	29	78.38%	5	13.51%
	At non peak hours (9:00-16:00, 18:30-6:30)	**85**	8	9.41%	67	78.82%	10	11.76%

Table 6.8: Descriptive statistics of tram-VRU accidents

In table 6.8, connections between the design or the volume of VRUs and the accidents are sought. Semi-exclusive alignments have the highest share of fatal accidents, while in tram/pedestrian malls of Amsterdam, fatal accidents had not appeared until December 2017. Exclusive alignments can be correctly characterized as safer, since only one crash between a tram and a pedestrian was observed in the study decade. The existence of a tram stop does not really affect accident numbers. It seems that locations near tram stops are slightly more dangerous compared to locations away from them. More accidents have been observed near protected crossings; however, the share of fatal accidents near unprotected crossings is the highest. In sections near cycle lanes with very low cycling intensity (i.e. less than 20 cyclists), only 5 accidents were reported; yet, 2 of them were fatal. The absolute number of accidents between trams and cyclists increases, as the cycling intensity rises from Level A to C. On the contrary, the proportion of fatal accidents drops. In Level D (i.e. >500 cyclists), the share of fatal accidents is similar to that in Level B, but the percentage of accidents with minor injuries is the highest. In attraction poles, where the flow of pedestrians (mainly tourists) is higher, the share of fatal accidents is low. Inside the Centrum (i.e. central district of Amsterdam), fatal accidents have not been reported yet. The percentage of accidents with minor injuries inside this district is the biggest compared to all the other categories of all the other categorical variables that are presented in table 6.8. Lastly, more crashes were observed during non-peak hours.

Table 6.9 gives some statistical trends regarding the risk levels of each different section. The number of accidents per km in the decade 2010-2017 that occurred in Amsterdam is used as a risk indicator. More accidents per km (4.639 accidents/km) appeared in tram/pedestrian malls, while in semi-exclusive alignments, more fatalities per km (0.297 fatal accidents/km) were observed. The previous rate is also high in sections near tram stops. Sections without crossings are safer, because all the corresponding rates are quite low. In this analysis, segments with unprotected sections reported slightly lower risk levels compared to segments with protected crossings. The highest risks were observed in sections near attraction poles. There, the fatal accidents and the accidents with severe injury(ies) per km are 0.416 and 5.617, respectively. Most of the attraction poles are located in the Centrum; this is why sections inside it reported a very high rate of crashes per km, equal to 3.863. Yet, there is no record about fatal accidents inside the Centrum and the rate that corresponds to minor injury(ies) is relatively low, i.e. 0.381.

		Total accidents (2007-2017)	Length (km)	Accidents per km (2007-2017)			
				Total	Fatal	Severe injury(ies)	Minor injury(ies)
Alignment Type	Exclusive	1	10.324	**0.097**	0.000	0.097	0.000
	Semi-exclusive	29	23.602	**1.229**	0.297	0.847	0.085
	Mixed traffic operations	82	60.601	**1.353**	0.066	1.089	0.198
	Tram/pedestrian mall	10	2.131	**4.693**	0.000	4.224	0.469
Tramstop	With tramstop in the next 100 m	65	44.013	**1.477**	0.159	1.113	0.204
	Without tramstop in the next 100 m	57	52.645	**1.083**	0.076	0.893	0.114
Pedestrrian /cycling crossing	Without crossing in the next 50 m	32	119.275	**0.268**	0.017	0.210	0.042
	With unprotected crossing in the next 50 m	22	23.912	**0.920**	0.125	0.711	0.084
	With protected crossing in the next 50 m	68	46.530	**1.461**	0.129	1.161	0.172
Attraction pole	Next to an attraction pole (buffer zone radius = 150 m)	33	4.807	**6.866**	0.416	5.617	0.832
	Away from an attraction pole (buffer zone radius = 150 m)	89	91.851	**0.218**	0.098	0.751	0.120
Districts	In the Centrum	36	18.382	**3.863**	0.000	1.578	0.381
	Outside of the Centrum	86	78.276	**0.332**	0.141	0.856	0.102

Table 6.9: Tram-VRU accidents per km

6.3.2. Spatial patterns

By performing a black spot analysis in GIS environment, spatial patterns related with the accidents between tram and VRUs reported in Amsterdam in the decade 2007-2017 can be pointed out. The planar Kernel density (i.e. density in the homogeneous 2-D Euclidean space) was estimated 6 times and the network Kernel density (i.e. density in the 1-D network space) was estimated 3 times. Three different bandwidths, namely of 100, 200, 300 m, were chosen to perform black spot analysis in different scales. For all the bandwidth levels, the planar Kernel density was estimated twice: 1) without attribute weights and 2) with attribute weights. As it has been pointed out, there is no GIS tool able to estimate network Kernel density with weights. The output of the planar KDE, weighted planar KDE and network KDE are presented in figures: 6.11, 6.12 and 6.13, respectively.

Figure 6.11: Black spot analysis using planar KDE

Through the observation of the map extracted from the planar KDE without the introduction of weights and with a bandwidth equal to 300 m, it can be said that accidents are concentrated in the tram section that starts at the Central Station of Amsterdam and ends in Dam Square. In the same map, black spots also appear next to Vondelpark and Museumplein. When using a smaller bandwidth equal to 200 m, it is obvious that many tram collisions with VRUs appear mainly in the Damrak street and not in Stationplein. Indeed, in 557 meters, which is the length of this central street, 9 severe accidents occurred in the decade 2007-2017. With a bandwidth equal to 100 m, a noticeable black spot is presented next to the entrance of Vondelpark.

By adding weights related with the severity of each accident (the weight values are presented in sub-chapter 3.3.2), the black spots seem to ”move” outside of the Centrum. A noticeable black spot is located in Osdorp in Tussen Mer street between the stations: Baden Powellweg and Hoekemens. Specifically, in the previous street, 2 fatal accidents and 2 accidents with severe road injuries have been reported in a line segment of 1156 meters. In Tussen Mer street, the tram alignement is semi-exclusive and the number of pedestrian/cycling crossings in the previously mentioned segment is 16. One tram crash with a fatality and one crash with a severe road injury was observed in another small (i.e. length equal to 583 m) semi-exclusive section between Louwesweg and Laan v. Vlaanderen stations. Another problematic spot is the junction van Baerlestraat-Paulus Potterstraat-Willemsparkweg near the Stedelijk Museum. There, the movements of trams are controlled by traffic lights and the tram track is shared with the motorized traffic. This spot is located next to an attraction pole and outside of the Centrum.

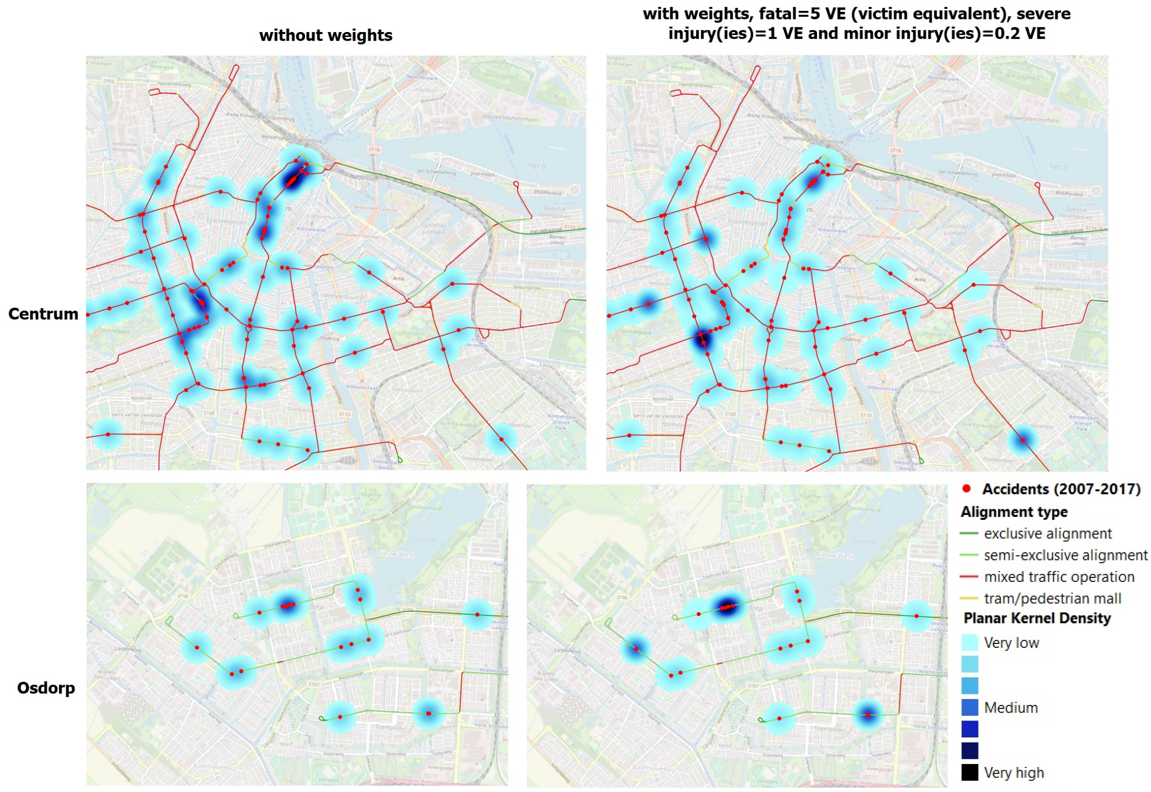

Figure 6.12: Black spot analysis using planar KDE (zoom-in)

In figure 6.13, in z-axis, the network Kernel density is given, while in the x-y plane, the tram network of Amsterdam has been added. By looking at the spatial patterns extracted from the network KDE, it can be concluded that tram crashes with VRUs ”follow a route” that starts at the Central Station of Amsterdam and ends at Museumplein. Streets, like: Damrak, Rokin and Leidsestraat, and crowded squares, such as: Dam Square and Leidsplein, are located along this route. All the previously mentioned places attract a lot of visitors in Amsterdam every day; therefore, the volume of VRUs is relatively high at these locations (i.e. more exposure). On the contrary, in Osdorp, the volume of VRUs is definitely much lower compared to the Centrum. The network Kernel density, especially in Tussen Mer street, has been estimated as one of the highest in the network. Another problematic spot, which is pointed out from the network KDE, is located next to the De Boelelaan tram stop. In this location, the tram alignment is semi-exclusive and all the crossings are controlled by traffic lights.

At this point, it should be mentioned that the junction Stadhouderskade-Hobbermastraat is the one with the highest concentration of accidents. A relatively high flow of cyclists (cycling intensity equal to 555), which goes to or comes from Hein Denner Brug, crosses the tram line at this location. In Stadhouderskade, the tram track is semi-exclusive, while in Hobbermastraat, it is shared with buses. The streams of the junction are controlled by traffic lights and the flow of pedestrians is very high, since the entrance to Vondelpark is located there. All these conditions seem to create an unsafe road environment, in which 3 crashes with severe injuries and 1 crash with minor injuries were reported in the decade 2010-2017.

In all the locations where the tram track is shared with pedestrians, tram-VRU accidents have been observed. In Dam square, two accidents with severe injuries were reported in the study decade and in Staionplein, one accident was reported. Leidsestraat is the only street where the tram line is fully shared with pedestrians. In 638 m (the length of Leidsestraat), 4 accidents have been recorded by the police. Lastly, in Rembrandtplein, two accidents with severe road injuries have been recorded.

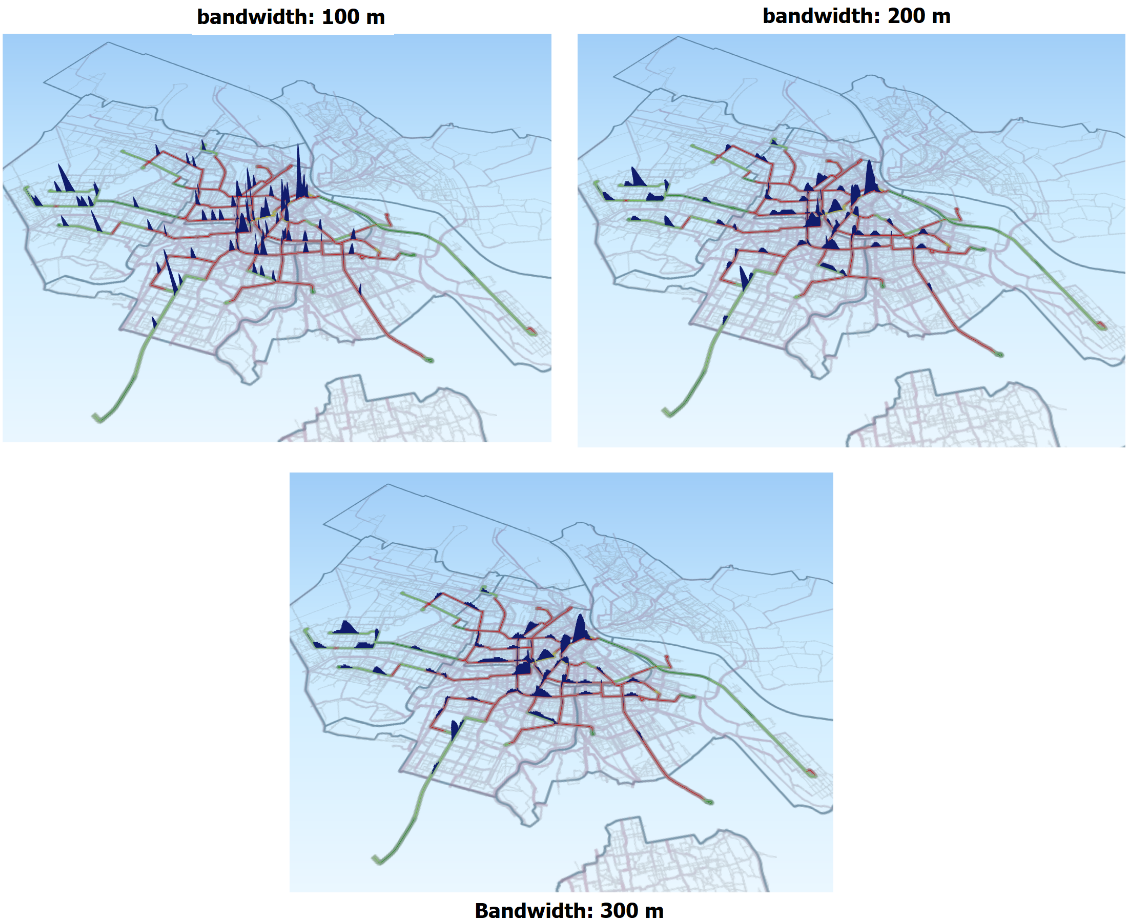

Figure 6.13: Black spot analysis using network KDE

6.4. Conclusions

Perceived safety and driving stress was rated 14 and 12 times respectively by 48 tram drivers of Athens. The majority of them are male and their age is between 31-50 years. They have been driving in the tram network of Athens for more than 10 years. The sample of tram drivers is representative, since the previously mentioned demographic characteristics of the sample do not differ significantly from how thing are in reality (i.e. demographics of all tram drivers of Athens).

The alignment type was assessed by the tram drivers as the most important factor of perceived safety with a mean score 5.7/7 (see figure 5.6). The factor related with the number of VRUs in the road environment has similar importance in relation with the previous one (i.e. mean score 5.5/7). On the contrary, the existence of a station is not an important parameter (i.e. mean score 3.3/7), according to the tram drivers. Furthermore, the lack of situational awareness and the unpredictable behavior of pedestrians were recommended by the tram drivers as additional factors that should be considered in the analysis. The contribution of familiarity to perceived safety rating was evaluated by comparing given ratings between two scenarios, which only differ in the level of familiarity. According to the descriptive statistics of the rating differences (mean rating difference equal to 0.526 and mode rating difference equal to 0), the level of familiarity did not influence, as much as expected, the perceived safety ratings.

According to the estimated ordinal regression model of perceived safety, the volume of VRUs in the road environment mainly influences perceived safety (statistical significant parameter for a 99% confidence interval). Tram/pedestrian malls and mixed traffic alignments (negative beta parameters) are less safe compared to semi-exclusive alignments. Sections with protected crossings were assessed as safer in comparison with sections with unprotected crossings or without crossing. The highest odds ratio that is equal to 5.392 was observed in the factor related with unprotected crossings; there is high heterogeneity in how much perceived safety is influenced by the existence of unprotected crossings (see figure 6.5). In addition, it was noted that there is no statistically significant difference in terms of safety between semi-exclusive alignment located in the middle of the street and the one located near the sidewalk. Indeed, the align3 parameter was proved statically insignificant for a 95% confidence interval, as it can be seen in table 6.3. The standard deviations of all the beta parameters were proved statistically significant for a confidence interval of 99%; therefore, all betas were correctly selected to be random parameters.

In the assessment of driving stress factors, perceived safety was assessed as the most important one, with a mean score 5.9/7, by the tram drivers. Yet, the last mentioned parameter was proved statically insignificant for a 95% confidence interval in all the estimated driving stress models (see more in Appendix C). Familiarity instead of perceived safety was introduced in the model function of driving stress. Familiarity together with arrival delay and load of standing passengers are the statistically significant parameters of driving stress for a confidence interval of 95% (see table 6.5). The highest odds ratio (equal to 4.086) was reported in the familiarity factor. The standard deviations of arrival delay and load of standing passengers parameters were proved to be statically significant for 98% confidence interval (see table 6.5); thus, they were correctly selected to be random. On the contrary, the majority of tram drivers agree that driving stress is increased when they are driving in unfamiliar sections, since the standard deviation of this parameter was statistically insignificant.

The objective safety using accident records was analysed in the tram network of Amsterdam. In the decade 2007-2017, 122 tram-VRU accidents were reported, i.e. 11.09 accidents per year. In the 87.71% of these recorded crashes, the VRU was either severely injured or died. Pedestrians are much more vulnerable compared to cyclists and moped riders, since in 7 out 11 fatal events, a pedestrian died. By estimating the number of accidents per km of each section, tram/pedestrian malls reported a relatively high number (i.e. 4.693 accident/km). Yet, in semi-exclusive alignments, more fatal crashes (7 out 11 total accidents) were observed in the decade 2007-2017. It is obvious in the black spot analysis that tram-VRU accidents are concentrated around touristic attraction poles of Amsterdam, such as: Damrak, Dam square, Vondelpark and Museumplein, where the flow of VRUs is expected to be quite high. However, inside the city center of Amsterdam, no fatal accidents were reported (see tables 6.7 and 6.9).

Figure 6.14 shows the share of scenarios that reported lower than level 4 perceived safety for each alignment type which appears in the tram network of Athens. Figure 6.15 examines the objective safety for each alignment type appearing in the tram network of Amsterdam in the three dimensions of traffic safety (i.e. risk, exposure and consequences). Both figures summarize the trends which were described in the previous paragraphs. Tram pedestrian malls have the highest share of subjectively unsafe driving scenarios in Athens and the highest number of accidents per km in Amsterdam; yet, no fatal accidents have been reported in the sections with this alignment type in Amsterdam. On the other hand, scenarios in Athens with semi-exclusive alignment were assessed as safer (i.e. perceived safety levels 4/7 and 5/7) by the tram drivers; yet in Amsterdam, the majority of fatal accidents appeared in semi-exclusive tram tracks.

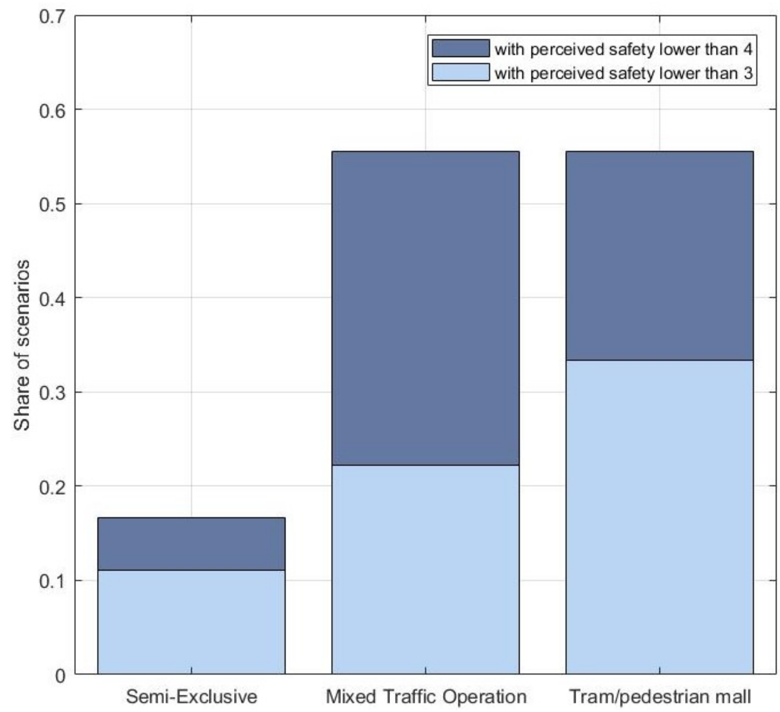

Figure 6.14: Share of scenarios with low perceived safety per alignment type (Athens)

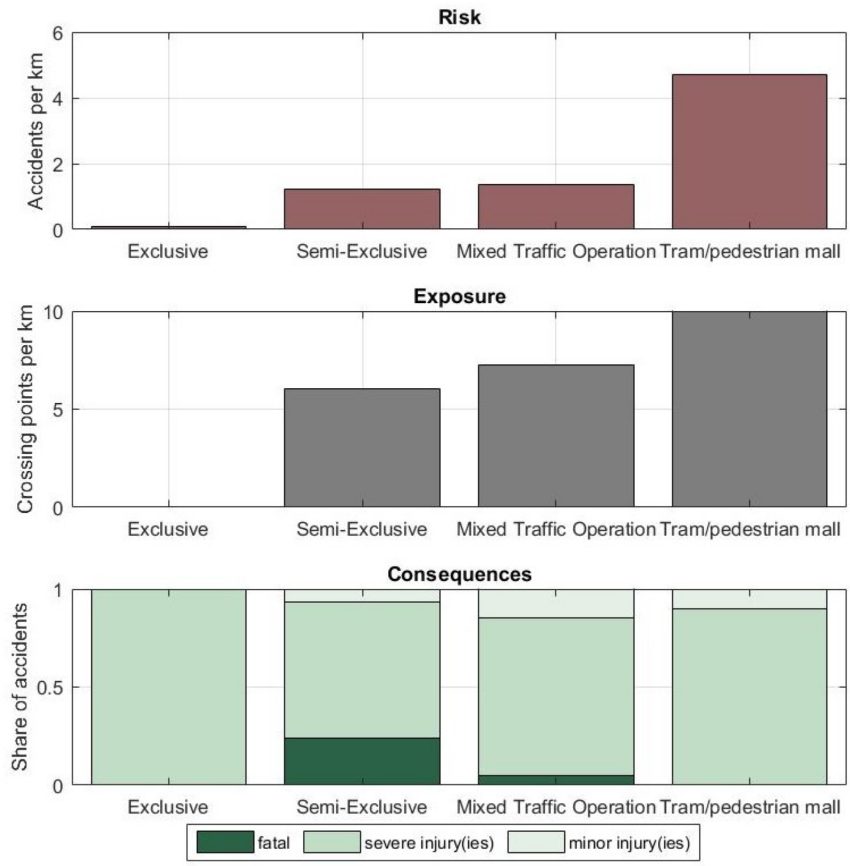

Figure 6.15: Objective safety per alignment type examined in the three dimensions of traffic safety (Amsterdam)

7
Discussion

By considering the previously presented results from all the different perspectives, the main objective of this chapter is to answer one by one the research questions, which were formulated in chapter 3. Next, these findings have to be utilized in order to propose measures that can reinforce safety without downgrading efficiency (second objective). In the section of practical recommendations, a consistent tram line design is developed. Afterwards, the study limitations are presented. Future research to overcome the limitations of this study and to examine the uncovered perspectives of tram safety are given in the last paragraph of this thesis.

7.1. Main findings

Important findings related with perceived safety and driving stress of tram drivers were obtained from the stated preferences survey that was conducted in Athens. Statistically significant parameters of perceived safety are: 1) alignment type, 2) existence and level of protection of pedestrian crossings and 3) volume of Vulnerable Road Users (VRUs) in the road environment. The existence of a tram stop in a section does not downgrade perceived safety, as it was expected. In tram stop sections, the volume of VRUs is usually quite high; at the same time, the tram speed is very low in these sections. According to the views of tram drivers of Athens, tram/pedestrian malls and mixed traffic alignments are less safe compared to semi-exclusive alignments located either in the middle of the street or near the sidewalk. Yet, tram drivers in Athens are unfamiliar with driving many kilometers of non-exclusive alignments, which mainly appear in the new section in Piraeus that has not yet been delivered. Familiarity as a factor did not influence significantly the perceived safety ratings. The subjectivity in perceived safety ratings is captured through the existence of random beta parameters in the final estimated model. High heterogeneity appeared in the beta parameters related with the existence and the type of pedestrian crossings; this means that not all tram drivers have the same opinion on whether the existence of an unprotected crossing in a section causes low perceived safety. On the contrary, there is a higher level of agreement regarding the impact of the factor related with the volume of VRUs in perceived safety.

Driving stress is a more subjective notion compared to perceived safety, since the range of given ratings was the highest for a 7-point Likert scale, i.e. equal to 6, in the majority of the presented driving scenarios. According to the coputed model, factors that influence driving stress are: 1) arrival delay, 2) load of standing passengers and 3) familiarity. As it has been mentioned in the study of Naznin et al. (2017), on-time running adds extra pressure to tram drivers. Yet, in Athens, very high values of arrival delay, e.g. 25 minutes, were proposed by the trainers of the tram drivers to be used in the questionnaire survey in order to test the relationship with stress levels. The tram system of Athens cannot be characterized as very reliable and it seems that tram managers do not push tram drivers to perform better. In other tram companies, pressure is possible to be higher and therefore the correspondent odds ratio may be estimated equally higher. The load of standing passengers is a statistically significant factor, though not so important compared to the other factors of driving stress. Usually, the tram driver is driving in a cabin that is separated from the cabin of passengers; therefore, he does not exactly know how many passengers and especially how many standing passengers are inside. One unexpected result was that perceived safety, as it is estimated by the model, does not really affect driving stress, while route familiarity does. One explanation for it is that experienced tram drivers believe that they are ready to respond properly in a (subjectively) unsafe section, if they are familiar with it. If there is no familiarity, the tram driver lacks confidence and therefore the driving stress is increased. Among the three statistically significant parameters of driving stress, familiarity is the only non-random. This means that tram drivers absolutely agree that driving stress is increased, when they are driving in unfamiliar sections.

Through the examination of accident records from Amsterdam (time period 2010-2017), it was observed that tram-VRU accidents are very rare (i.e. 11.09 tram-vru accident per year). This conclusion is in line with previous relevant studies, such as: SWOV (2011) in the Netherlands and Marti et al. (2016) in Switzerland. The small sample size (i.e. 122 tram-VRU accidents) did not allow the estimation of accident severity models, where the relationship between design and accident severity would be examined. Accident records from more than one tram networks are required to estimate statistically significant correlations between objective safety and design factors. Yet, this dataset was useful in order to point out some interesting statistical trends and spatial patterns. Black spot analysis was proved a very suitable method in order to determine the locations, where tram accidents are concentrated in Amsterdam using this admittedly limited dataset.

The most probable outcome from a crash between a tram and VRU in the tram network of Amsterdam is the severe injury of the VRU (i.e. 96 accidents with severe road injuries out of total 122). The statistical analysis showed that pedestrians are much more vulnerable compared to cyclists and riders of mopeds, i.e. out of 11 casualties, 7 were pedestrians, 1 was a moped rider and 3 were cyclists. Tram collisions with VRUs are much more frequent in tram/pedestrian malls. In the semi-exclusive alignments, the number of fatal accidents per km was the highest compared to the other alignment types. This spatial pattern is in line with the binary logit model developed by Naznin et al. (2016), where the existence of lane priority and as a result higher tram velocities increase the likelihood of a fatal accident. Yet, only 1 tram accident was observed considering the years 2007-2017. Another significant trend is that more crashes between trams and pedestrians appear near the touristic attraction poles of Amsterdam, where the flow of pedestrians is relatively high. Yet, inside the city center of Amsterdam, no fatal accidents were recorded in the decade 2007-2017.

By comparing the results obtained from stated preferences survey conducted in Athens and the ones from the accident analysis conducted in Amsterdam, there are not so many differences between perceived safety and objective safety, as it was expected. Scenarios with tramways shared with pedestrians were assessed by the tram drivers of Athens as very unsafe. Simultaneously, the number of accidents with severe road injuries per km that occurred in this non-exclusive alignment type (i.e. tram/pedestrian mall) in Amsterdam was by far the highest. As it has been mentioned, the number of VRUs in the road environment downgrades perceived safety; in Amsterdam, tram-VRU accidents were concentrated around touristic attraction poles, where the flow of pedestrians is relatively high. One important difference between perceived safety and objective safety lies in semi-exclusive alignments. Tram drivers of Athens assessed this alignment type as much safer compared to other types; however, in Amsterdam, 7 out of 11 fatal accidents were observed in sections with semi-exclusive alignment. In these sections, the average tram speed is surely higher than 30 km/h. Furthermore, the accidents analysis showed that there is no great difference in terms of safety risks between mixed traffic and semi-exclusive alignments. Some tram drivers of Athens (high heterogeneity) think that protected crossings improve traffic safety, but this view cannot be confirmed by the spatial analysis of accidents conducted in Amsterdam. To sum up, tram drivers seem to know well the potential dangerous points of the network. Discussions inside the tram companies about past accidents and training seminars helped them to be more aware of tram safety problems. They know well that high volume of pedestrians leads to many complex interactions, since the behavior of pedestrians is almost unpredictable.

7.2. Practical recommendations

The previously mentioned findings are utilized in this section, in order to propose practical measures that can reinforce tram safety. System efficiency and reliability are considered for the development of these proposals, since they are important factors of public transport systems.

In general, looking (again) at the results of this analysis, tram tracks that are fully shared with pedestrians are not recommended based on the results of this thesis. Due to the infinite number of crossing points, pedestrians are much more exposed, compared to all the other designs. As it was seen in the literature (Korve et al., 2001; SWOV, 2011; Marti et al., 2016) and in the accident analysis, a severe road injury of a VRU is by far the most probable outcome from a collision with a tram. The share of fatal accidents in which a pedestrian was involved was the highest in comparison with the other active modes. Furthermore, more severe accidents per km were observed in tram/pedestrian malls. According to the results of the survey, tram drivers feel more unsafe when they are driving in this type of alignment; consequently, they reduce tram speed. Due to the many and complex interactions between trams and pedestrians, more emergency brakings may be observed in tram/pedestrian malls. Therefore, the average speed of the tram inside the pedestrianized zones is expected to be inversely proportional to the volume of VRUs. This fact increases the unreliability of the tram system, while this is operating in these urban areas. In addition, due to the very low velocities, trams need more time to cross city centers in comparison with the other urban transport modes, such as: metro, bus and cars, which do not operate in pedestrianized zones.

Surely, the previous recommendations about tram/pedestrian malls contradict the views of many urban planners throughout the world. They rightly argue that tramways are able to transform city centers and make cities more livable through the many urban regeneration projects that are associated with the construction of a tramway (van der Bijl et al., 2018). In addition, the existence of a tram line in pedestrianized zones increases the accessibility and the coverage of the tram network. One good solution might be the utilization of bicycles and new micro-mobility modes (e.g. e-scooters) for the access to or egress from public transport stations/stops, which will be located some meters outside the zones dedicated to pedestrians. Pedestrianized zones are recommended to be a safe place for comfortable walking or cycling and trams should be separated from VRUs flows. In semi-exclusive or mixed traffic operations sections located around central pedestrianized zones, the trams will start moving faster; consequently, the system effectiveness will be improved and more travellers will choose it for their daily trips.

In some locations of several networks of the world, it may not be feasible to provide complete separation between trams and VRUs flows, as Marti et al. (2016) has mentioned. The development of a consistent design of a tram line may be proved as a very interesting proposal. Perceived safety, as it can be computed by the estimated model, and especially the difference in the level of perceived safety from one section to the other can be utilized as an indicator to describe design inconsistencies. The previous idea is valid under the assumption that tram drivers adopt the tram speed based on their safety feeling. Therefore, it does not contradict previous studies about design consistency (Ng and Sayed, 2004; Torregrosa et al., 2013), which used speed deviations as a main indicator. Figure 7.1 can be utilized as a theoretical paradigm; it shows a single tram line, which connects two suburban areas through the city center. The level of tram line separation is reduced gradually, as the tram goes from the outskirts to central urban places. Exclusive and semi-exclusive alignments should be preferred in the outskirts. In these types of alignments, the design speed should be between 50-70 km/h. In exclusive sections, the tram track will be protected by fences and there will not be pedestrian/cycling crossings. Few pedestrian/cycling crossings are allowed in semi-exclusive sections, in particular locations like junctions or spots next to tram stops. These crossings could be protected by automatic (or manual) gates and traffic lights, and offset pedestrian crossings could ideally be established near tram stops. On the other hand, unprotected pedestrian crossings located in the middle of a semi-exclusive section are surely very dangerous, as they are inconsistent with the semi-exclusive design. Indeed, according to the developed model, semi-exclusive alignments increase perceived safety, while the existence of an unprotected crossing results in the decrease of perceived safety. More crossing points could appear in the tram sections that are located in the city center, since the volume of VRUs is higher. Traffic lanes shared with buses or with motorized traffic are a suitable design for central areas if one takes into account the lack of available urban space inside them. Lower operational speeds (around 30 km/h) and pedestrian/cycling crossings, which would be protected by the presence of traffic lights in junctions, could reinforce safety. Inside the pedestrianized zones, audible warning systems are recommended, so that pedestrians will be informed about the tram passages. The tram speed should drop to 20 km/h in tram/pedestrians malls.

Regarding the mitigation of stress of tram drivers, the same approach is followed, as it can be seen in figure 7.2. Due to the increased number of interactions that occur in the non-exclusive alignments located in the city center, the delay probability increases. High delay means more driving stress, according to the estimated driving stress model. It is advisable that tram managers consider this parameter in their schedules by providing additional time margins. Additionally, the pressure on the

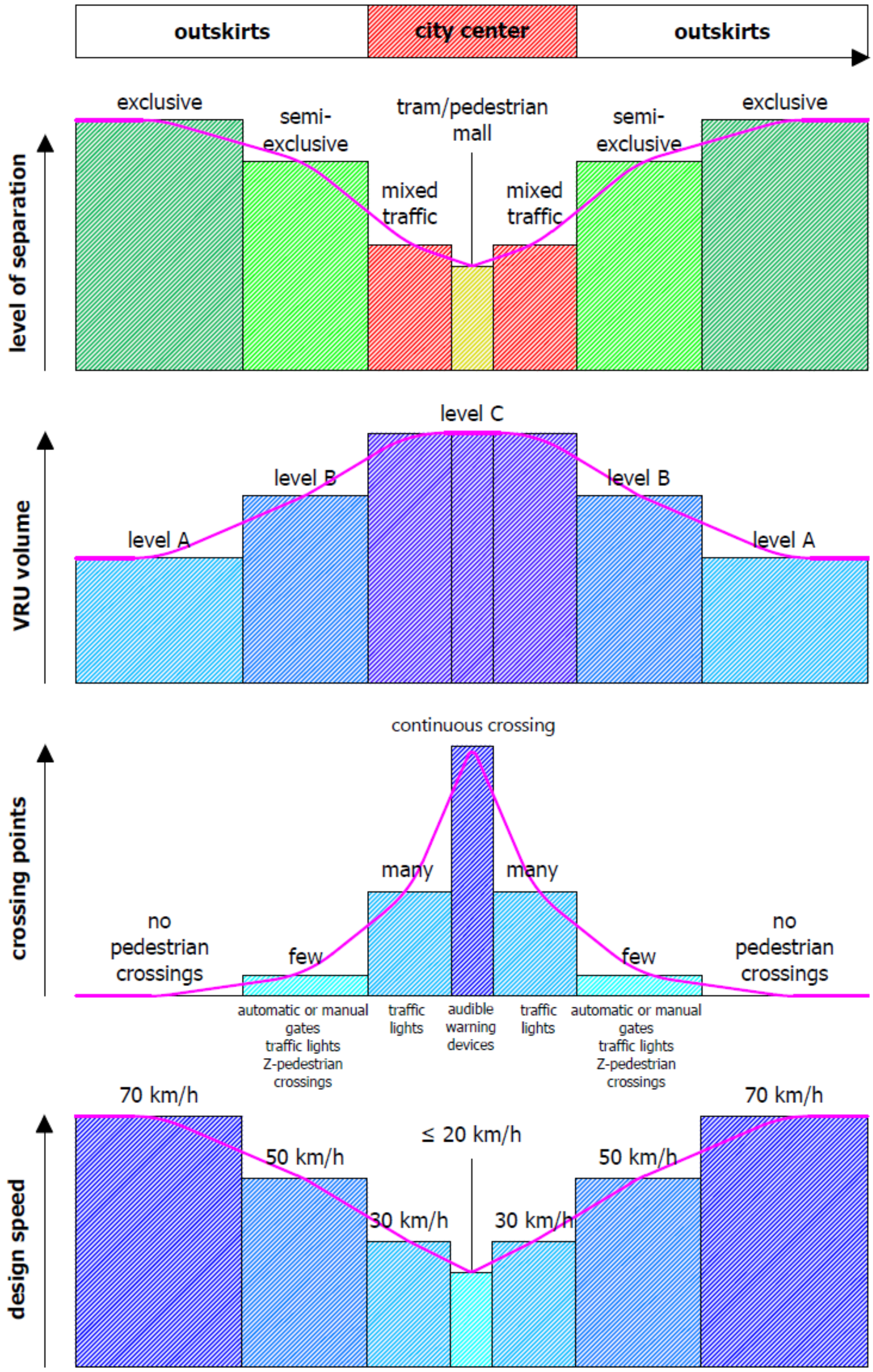

Figure 7.1: Development of a consistent tram line design (1)

tram drivers for on-time running in these sections had better be minimized in the future. On the contrary, the schedules regarding the tram operations outside the city center in exclusive or semi-exclusive alignments, are recommended to be stricter. Driving stress is slightly influenced by the number of (standing especially) passengers. Higher load of standing passengers inside the tram usually exists between the central tram stops of each city. Higher frequencies can mitigate this problem; yet, the capacity of the tram infrastructure inside the city center is limited.

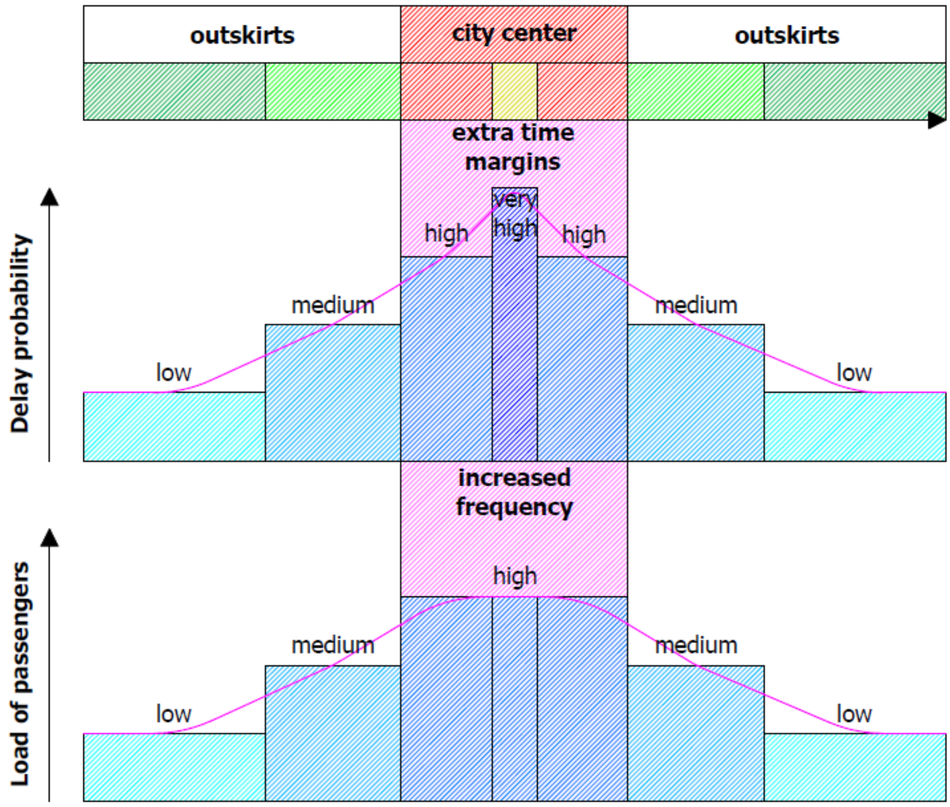

Figure 7.2: Development of a consistent tram line design (2)

The results also showed that route familiarity is the most important parameter of driving stress. Tram managers ought to consider this factor in tactical and operational planning. One idea is to use experienced tram drivers for itineraries during peak hours. Good training using simulations is a recommended solution for the inexperienced tram drivers, who are not familiar with the routes of the network. Furthermore, discussions regarding the safety of the tram network inside the tram company are bound to increase the situational awareness of the tram drivers and therefore, the differences between objective and subjective safety will be minimized further more.

7.3. Study limitations

In order to extract significant scientific results about tram safety, the author of this thesis had to cooperate with a tram company. Definitely, it was not an easy process to find one or more tram companies that were willing to take part in the present study. To facilitate the process of finding a tram company, some experiments/procedures, such as heart rate measurements, collection of speed profiles and identification of emergency braking location using accelerometers, which had been included in the research proposal, were discarded from this analysis. Generally speaking, this study presents results, conclusions and practical recommendations on a more macro scale (i.e. tram network level) and not on a micro scale (i.e. junction/street level). Surely, the previously mentioned procedures would allow the author to analyse tram safety problems, in particular locations of the study tram network. Lastly, the results which are presented in this analysis refer to the study cases only; yet, until now, it is not certain if these study cases (i.e. Amsterdam and Athens) are representative and adequate in order to export scientific conclusions that are valid globally.

In the survey, the independent variables were selected based on the findings of previous studies conducted in Melbourne, Australia, such as: Naweed and Rose (2015) and Naznin et al. (2017). No interviews with the tram drivers of Athens were carried out in order to collect more qualitative pieces of information that would be relevant with the study network, i.e. Athens. In addition, some important parameters related with perceived safety, like the design consistency or the complexity of interactions, and others related with stress, like fatigue, were excluded from the analysis, because it was not feasible to describe some of them in a survey form. Simultaneously, the agreement with the tram company of Athens was for a 10-minute survey, which means fewer scenarios, so fewer parameters. In Athens, the majority of pedestrian crossings that exist along tram lines are not controlled by traffic lights or another system; therefore, the tram drivers had to imagine (as it was asked in the survey form) that the unprotected crossing in the picture is now protected in order to rate some scenarios with protected crossing. Few kilometers of non-exclusive alignments (i.e. tram/pedestrian mall and mixed traffic operations) exist in the present network of Athens; therefore, perceived safety in familiar (to tram drivers) non-exclusive sections was not assessed, as much as it should.

Regarding the objective safety, the lack of a complete dataset of tram accidents in Athens was an important limitation, which did not allow the author to compare objective safety with perceived safety in a single network. In the meantime, owing to very busy schedules, the tram company of Amsterdam was unable to accept the request of the author to conduct a stated preferences survey. The small number of reported tram-VRU accidents in Amsterdam did not allow the development of statistical models that could examine the relationships between design factors and accident severity. In addition, as it has been mentioned, the spatial analysis of accidents was conducted on a macro scale, due to uncertainty regarding the exact location of a tram-VRU crash. Furthermore, the black spot analysis was based on accident records that came from only one source of information (i.e. BRON database). Past studies (Naznin et al., 2016; Naznin and Currie, 2018) have remarked some important differences among datasets from different sources. Only primary collisions between tram and VRUs were included in this dataset and there was not any evidence regarding the accidents, in which tram was involved as a third party. Google Earth images instead of drawings were used in order to see the tram line design in the locations where each accident occurred. Lastly, no interviews/discussions were conducted with the infrastructure managers of Amsterdam in order to acquire qualitative knowledge from their experiences regarding the tram safety problems and the problematic (or black) spots of this network.

7.4. Scientific recommendations

It is recommended that future research focus more on the tram drivers' behavior and psychology. Perceived safety of tram drivers could be used as one of the main indicators of tram safety, since tram accidents (objective safety perspective) are very rare and severe at the same time. An alternative approach is to identify traffic conflicts or near-misses by looking at traffic videos and estimating surrogate safety measures, like time to collision (TTC) and post encroachment time (PET). Yet, this analysis requires many hours of videos and the establishment of cameras in all the problematic spots of the network.

In this thesis, a methodological tool so as to examine perceived safety and driving stress was developed. In theory, this methodological tool seems suitable for other networks, with some small modifications; still, it needs to be tested and validated in practice. In the future, it can also be improved by adding some additional parameters, such as fatigue and complexity of interactions. One inspired idea would be to add live images instead of still images in order to give some clues to the respondents regarding the movements of pedestrians. Another idea is to examine the influence of design inconsistencies to driving stress inside the survey. Hypothetical differences of perceived safety levels will be used in order to describe this parameter in the questionnaire form. In the end, the respondent will rate if the transition from a safe design to an unsafe one increases further more his/her stress. In the future, it could be attempted to disconnect the questions related with driving stress from the questions related with perceived safety.

Future research should also focus on how factors related with daily operations influence the stress of tram drivers. As it has been mentioned by Naznin et al. (2017), tram drivers have to keep everyone safe, while they are trying to run on time. Possibly, the "taste" of delay regarding driving stress may differ among tram companies of the world. These differences may be relevant with the priorities and the culture of each tram company in general. The driving stress model is able to indicate how well each operator balances safety with efficiency. Fatigue is another factor that was not discussed in this thesis. It is related with the schedule of each company and with the complexity level of interactions faced by the tram driver every day in the different tram sections. Designs, that allow pedestrians to cross the tram tracks freely (i.e. tram pedestrian malls), may increase the workload of drivers and consequently their fatigue.

Driving stress of tram drivers can be quantified better through the use of Photoplethysmogram (PPG) sensors that are able to record the heart rate and the skin response. van Gent et al. (2018) have already executed this type of analysis in order to discuss car driving behavior. In the end, a stress profile would be created for all the tram lines of the study network. These profiles could be compared with speed and acceleration profiles, which can be obtained by tachographs and accelerometers respectively, in order to identify direct relationships between driving stress and performance. Furthermore, acceleration profiles combined with GPS data can point out the location of emergency braking points. Emergency braking points can be easily utilized as an indicator of objective tram safety, since they can prove the occurrence (though not the severity) of a conflict. Then, traffic safety could be examined on a micro scale (e.g. in junctions).

Regarding objective safety, accident records from one study network are not enough to develop statistical models, as it was proved in this analysis. One good recommendation is to include crashes in the analysis of more than 10 tram networks (10 networks * 100 tram-VRUs accidents per network = 1000 tram-VRU accidents), so that, models related with crash severity by using statistical techniques, such as ordered logit (or probit) or mixed logit, can be computed. As it was seen, the estimation of network kernel density can reveal some important spatial patterns. The existing network KDE tool could be upgraded by adding an option that would allow the introduction of weights connected with the attributes of one crash (e.g. crash severity). It is possible that the estimated kernel densities of a single network be used as the dependent variable of a statistical model. These recommended statistical models will be able to predict locations in the tram network with high concentration of tram accidents, by taking into account the design characteristics and the traffic conditions of these locations. This methodological approach has never been used in previous studies related with traffic safety; it is recommended that it be tested and validated in the future. In theory, it seems a quite suitable approach for collisions, which are rare and severe at the same time.

In conclusion, it is recommended that the importance of the public transport drivers' views in scientific research should be upgraded in the future. It is essential that public transport drivers' expertise and experiences be taken into consideration in the design of tram lines and in the assessment of safety along the latter. Many researchers of traffic safety or transport engineers are car drivers, but surely a quite big proportion of them have not driven a train or a tram or a bus in order to interpret better the daily challenges of the public transport drivers.

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A

Appendix: Survey form

A questionnaire survey about perceived safety and driving stress of tram drivers

Thank you for your interest to participate in this survey. It will take about 10 minutes to complete the survey.

The department of Transport and Planning at Delft University of Technology (TU Delft) in the Netherlands developed this survey in order to assess and finally estimate the subjective (or perceived) safety and the driving stress of tram drivers in different traffic situations in different tram networks of the world. One important case is the tram network of Athens.

In this survey, you as tram driver will assess the safety of different locations of the tram network in Athens under certain driving scenarios. Each location is presented by a photograph combined with a text underneath the picture, which describes the driving scenario, you need to consider. In addition, you will be asked to rate the level of driving stress, you might feel while driving the tram in each location. The total number of locations included in this questionnaire form is 11.

IMPORTANT
#1: Focus only on the Vulnerable Road Users (pedestrians, cyclists, etc.), that are presented in the pictures.

#2: In all the scenarios, imagine that the tram speed is lower than the speed limit of each section.

#3: Assume that you are driving in the morning and it is not raining.

Your opinion is very important to us!

Reasearch Team
Panagiotis G. Tzouras, MSc Student
Marjian Hagenzieker, Professor
Haneen Farah, Assistant Professor
Eleonora Papadimitriou, Assistant Professor
Niels van Oort, Assistant Professor

TU Delft

ΣΤΑΣΥ
ΣΤΑΘΕΡΕΣ ΣΥΓΚΟΙΝΩΝΙΕΣ Α.Ε.

Figure A.1: Page 1 of the online form

Picture 1

Scenario 35

You are here
Address: Eth. Antistaseos 8, Pireaus 18531, Attica, Greece

In this street, **the tramway is shared** with the **motorized traffic.**
The **green arrow** shows the **direction** of your tram.
There is **no station** in the next 50 m.
There is **no pedestrian crossing** in the next 50 m.
There are **as many pedestrians as** you see in the **image**.

How safe would you feel? Rate from 1 (very unsafe) to 7 (very safe)

Very unsafe (1)	2	3	Neutral (4)	5	6	Very safe (7)
○	○	○	○	○	○	○

If, in the previous conditions, you take into account that

you are **15 minutes late** compared to the scheduled arrival time to the next station,
all seats are occupied and the number of **standing passengers** is **72** (50% less than the tram standing capacity).

Rate from 1 (not stressful at all) to 7 (very stressful) the level of driving stress, you would feel.

Not stressful at all (1)	2	3	Moderate stress (4)	5	6	Very stressful (7)
○	○	○	○	○	○	○

Figure A.2: Page 2 of the online form

Picture 2

Scenario 16-19

You are here
Address: Aggelou Metaxa 17, Glifada 16675, Attica, Greece

In this location, **the tramway is separated** from the **motorized traffic** and it is located **in the middle** of the street.
The **green arrow** shows the **direction** of your tram.
There is **a station** in the next 50 m.
There is **an unprotected pedestrian crossing** (without traffic lights) in the next 50 m.
As you see in the image, there are **a few pedestrians** in your road environment.

How safe would you feel? Rate from 1 (very unsafe) to 7 (very safe)

Very unsafe (1)	2	3	Neutral (4)	5	6	Very safe (7)
○	○	○	○	○	○	○

If, in the previous conditions, you take into account that:

you are **5 minutes late** compared to the scheduled arrival time to the next station,
all seats are occupied and the number of **standing passengers** is **72** (50% less than the tram standing capacity).

Rate from 1 (not stressful at all) to 7 (very stressful) the level of driving stress, you would feel.

Not stressful at all (1)	2	3	Moderate stress (4)	5	6	Very stressful (7)
○	○	○	○	○	○	○

Now you know that:

you are **15 minutes late** compared to the scheduled arrival time to the next station,
all seats are occupied and there are **no standing passengers.**

Rate from 1 (not stressful at all) to 7 (very stressful) the level of driving stress, you would feel.

Not stressful at all (1)	2	3	Moderate stress (4)	5	6	Very stressful (7)
○	○	○	○	○	○	○

Figure A.3: Page 3 of the online form

Picture 3

Scenario 28

You are here
Address: Grigoriou Lampraki 69, Pireaus 18534, Attica, Greece

In this street, **the tramway is shared** with **pedestrians**.
The **green arrow** in the picture shows the **direction** of your tram.
There is **no station** in the next 50 m.
There is **no pedestrian crossing** in the next 50 m.
In your road environment, there are **as many pedestrians as** you see in the **image.**

How safe would you feel? Rate from 1 (very unsafe) to 7 (very safe)

Very unsafe (1)	2	3	Neutral (4)	5	6	Very safe (7)
○	○	○	○	○	○	○

If, in the previous conditions, you take into account that:

you are **15 minutes** late compared to the scheduled arrival time to the next station,
all seats are occupied and the number of **standing passengers** is **72** (50% less than the tram standing capacity).

Rate from 1 (not stressful at all) to 7 (very stressful) the level of driving stress, you would feel.

Not stressful at all (1)	2	3	Moderate stress (4)	5	6	Very stressful (7)
○	○	○	○	○	○	○

Figure A.4: Page 4 of the online form

Picture 4

Scenario 31

You are here
Address: Leof. Posidonos 48, Alimos 17455, Attica, Greece

In this street, **the tramway is separated** from the **motorized traffic** and is located **next to the sidewalk**.
The **green arrow** shows the **direction** of your tram.
There is **a station** in the next 50 m.
There is **no pedestrian crossing** in the next 50 m.
In your road environment, there are **as many pedestrians as** you see in the **image**.

How safe would you feel? Rate from 1 (very unsafe) to 7 (very safe)

Very unsafe (1)	2	3	Neutral (4)	5	6	Very safe (7)
○	○	○	○	○	○	○

If, in the previous conditions, you take into account that:

you are **25 minutes late** compared to the scheduled arrival time to the next station,
all seats are occupied and the number of **standing passengers** is **72** (50% less than the tram standing capacity).

Rate from 1 (not stressful at all) to 7 (very stressful) the level of driving stress, you would feel.

Not stressful at all (1)	2	3	Moderate stress (4)	5	6	Very stressful (7)
○	○	○	○	○	○	○

Figure A.5: Page 5 of the online form

Picture 5

Scenario 10

You are here
Address: Kasomouli 24, Athina 11745, Attica, Greece

In this street, **the tramway is sepated** from the **motorized traffic** and is located **next to the sidewalk.**
The **green arrow** shows the **direction** of your tram.
There is **no station** in the next 50 m.
There is **an unprotected pedestrian crossing** (without traffic lights) in the next 50 m.
In your road environment, there are **as many pedestrians as** you see in the **image.**

How safe would you feel? Rate from 1 (very unsafe) to 7 (very safe)

Very safe (1)	2	3	Neutral (4)	5	6	Very Unsafe (7)
○	○	○	○	○	○	○

If, in the previous conditions, you take into account that:

you are **15 minutes late** compared to the scheduled arrival time to the next station,
all seats are occupied and the number of **standing passengers** is **143** (value equal to the tram standing capacity).

Rate from 1 (not stressful at all) to 7 (very stressful) the level of driving stress, you would feel.

Not stressful at all (1)	2	3	Moderate stress (4)	5	6	Very stressful (7)
○	○	○	○	○	○	○

Figure A.6: Page 6 of the online form

Picture 6

Scenario 22

You are here
Address: Machis Analatou 62, Athina 11744, Attica, Greece

The tramway is **separated** from the **motorized traffic** and is located in the **middle** of the street.
The **green arrow** shows the **direction** of your tram.
There is **no station** in the next 50 m.
The **pedestrian crossing** in front of you **is protected** by **traffic lights**, which inform pedestrians about tram passages.
In your road environment, there are **as many pedestrians as** you see in the **image.**

How safe would you feel? Rate from 1 (very unsafe) to 7 (very safe)

Very unsafe (1)	2	3	Neutral (4)	5	6	Very safe (7)
○	○	○	○	○	○	○

If, in the previous conditions, you take into account that:

you are **15 minutes late** compared to the scheduled arrival time to the next station,
all seats are occupied and there are **no standing passengers.**

Rate from 1 (not stressful at all) to 7 (very stressful) the level of driving stress, you would feel.

Not stressful at all (1)	2	3	Moderate stress (4)	5	6	Very stressful (7)
○	○	○	○	○	○	○

Figure A.7: Page 7 of the online form

Picture 7

Scenario 24

You are here
Address: Leof. Posidonos 48, Alimos 17455, Attica, Greece

In this street, the tramway **is separated** from the **motorized traffic** and is located **next to the sidewalk.**
The **green arrow** shows the **direction** of your tram.
There is **no station** in the next 50 m.
Imagine that the **pedestrian crossing** in front of you **is protected** by **traffic lights,** which inform pedestrians about tram passages.
In your road environment, there are **as many pedestrians as** you see in the **image**.

How safe would you feel? Rate from 1 (very unsafe) to 7 (very safe)

Very unsafe (1)	2	3	Neutral (4)	5	6	Very safe (7)
○	○	○	○	○	○	○

If, in the previous conditions, you take into account that:

you are **5 minutes late** compared to the scheduled arrival time to the next station,
all seats are occupied and the number of **standing passengers** is **72** (50% less than the standing capacity of the tram).

Rate from 1 (not stressful at all) to 7 (very stressful) the level of driving stress, you would feel.

Not stressful at all (1)	2	3	Moderate stress (4)	5	6	Very stressful (7)
○	○	○	○	○	○	○

Figure A.8: Page 8 of the online form

Picture 8

Scenario 27

You are here
Address: Grigoriou Lampraki 89, Pireaus 18534, Attica, Greece

In this street, **the tramway is shared** with **pedestrians.**
The **green arrow** shows **the direction** of your tram.
There is **a station** in the next 50 m.
Imagine that the **pedestrian crossing** in front of you **is protected** by **additional traffic lights**, which inform pedestrians about tram passages.
There are **as many pedestrians as** you see in the **image**.

How safe would you feel? Rate from 1 (very unsafe) to 7 (very safe)

Very unsafe (1)	2	3	Neutral (4)	5	6	Very safe (7)
○	○	○	○	○	○	○

If, in the previous conditions, you take into account that:

you are **15 minutes late** compared to the scheduled arrival time to the next station,
all seats are occupied and there are **no standing passengers**.

Rate from 1 (not stressful at all) to 7 (very stressful) the level of driving stress, you would feel.

Not stressful at all (1)	2	3	Moderate stress (4)	5	6	Very stressful (7)
○	○	○	○	○	○	○

Figure A.9: Page 9 of the online form

Picture 9

Scenario 33

You are here
Address: Leof. Posidonos 48, Alimos 17455, Attica, Greece

In this street, the tramway is **separated** from the **motorized traffic** and it is located **next to the sidewalk**.
The **green arrows** in the pictures shows the **direction** of your tram.
There is **a station** in the next 50 m.
Imagine that **the pedestrian crossing** in front of you **is protected** by **traffic lights**, which inform pedestrians about tram passages.
In your road environment, there are **as many pedestrians as** you see in **both images**.

How safe would you feel? Rate from 1 (very safe) to 7 (very unsafe)

Very unsafe (1)	2	3	Neutral (4)	5	6	Very safe (7)
○	○	○	○	○	○	○

If, in the previous conditions, you take into account that:

you are **5 minutes late** compared to the scheduled arrival time to the next station,
all seats are occupied and the number of **standing passengers** is **143** (value equal to the tram standing capacity).

Rate from 1 (not stressful at all) to 7 (very stressful) the level of driving stress, you would feel.

Not stressful at all (1)	2	3	Moderate stress (4)	5	6	Very stressful (7)
○	○	○	○	○	○	○

Figure A.10: Page 10 of the online form

Picture 10

Scenario 101

You are here
Address: Kasomouli 50, Athens 11744, Attica, Greece

In this street, **the tramway is shared** with **pedestrians.**
The **green arrow** shows **the direction** of your tram.
There is **a station** in the next 50 m.
There is **an unprotected pedestrian crossing** (without traffic lights) in the next 50 m.
In your road environment, there are **as many pedestrians as** you see in the **image**.

How safe would you feel? Rate from 1 (very unsafe) to 7 (very safe)

Very unsafe (1)	2	3	Neutral (4)	5	6	Very safe (7)
○	○	○	○	○	○	○

Figure A.11: Page 11 (a) of the online form

Now, imagine that you are driving in the **new section: SEF-Pireaus**.

In this street, **the tramway is shared** with **pedestrians.**
The **green arrow** shows **the direction** of your tram.
There is **a station** in the next 50 m.
There is **an unprotected pedestrian crossing** (without traffic lights) in the next 50 m.
In your road environement, there are **as many pedestrians as** you see in the **image**.

How safe would you feel? Rate from 1 (very unsafe) to 7 (very safe)

Very unsafe (1)	2	3	Neutral (4)	5	6	Very safe (7)
○	○	○	○	○	○	○

If, in the last driving conditions, you take into account that:

you are **25 minutes late** compared to the scheduled arrival time to the next station,
all seats are occupied and the number of **standing passengers** is **143** (value equal to the tram standing capacity).

Rate from 1 (not stressful at all) to 7 (very stressful) the level of your driving stress, you would feel.

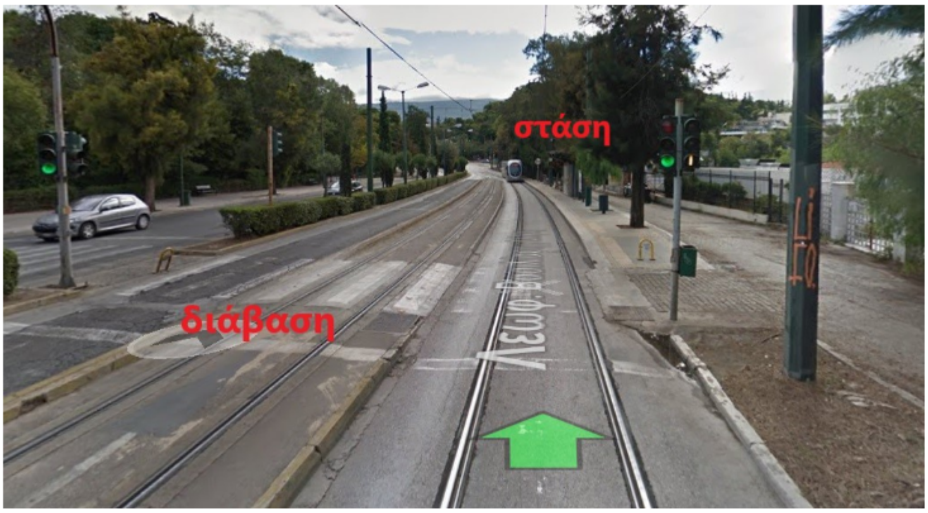
Not stressful at all (1)	2	3	Moderate stress (4)	5	6	Very stressful (7)
○	○	○	○	○	○	○

Figure A.12: Page 11 (b) of the online form

Picture 11

Scenario 115

You are here
Location: Leof. Vasilissis Olgas, Athina 10557, Attica, Greece



In this street, **the tramway is shared** with the **motorized traffic**.
The **green arrow** shows the **direction** of your tram.
There is **a station** in the next 50 m.
Imagine that the **pedestrian crossing** in front of you **is not protected** by **traffic lights.**
As you see in the image, there are **a few pedestrians** in your road environment.

How safe would you feel? Rate from 1 (very unsafe) to 7 (very safe)

Very safe (1)	2	3	Neutral (4)	5	6	Very unsafe (7)
○	○	○	○	○	○	○

Figure A.13: Page 12 (a) of the online form

Now, imagine that you are driving in the **new section: SEF-Pireaus**.

In this street, **the tramway is shared** with **the motorized traffic**.
The **green arrow** shows the **direction** of your tram.
There is **a station** in the next 50 m.
Imagine that the **pedestrian crossing** in front of you **is not protected** by traffic lights.
As you see in the image, there are **a few pedestrians** in your road environment.

How safe would you feel? Rate from 1 (very safe) to 7 (very unsafe)

Very unsafe (1)	2	3	Neutral (4)	5	6	Very safe (7)
○	○	○	○	○	○	○

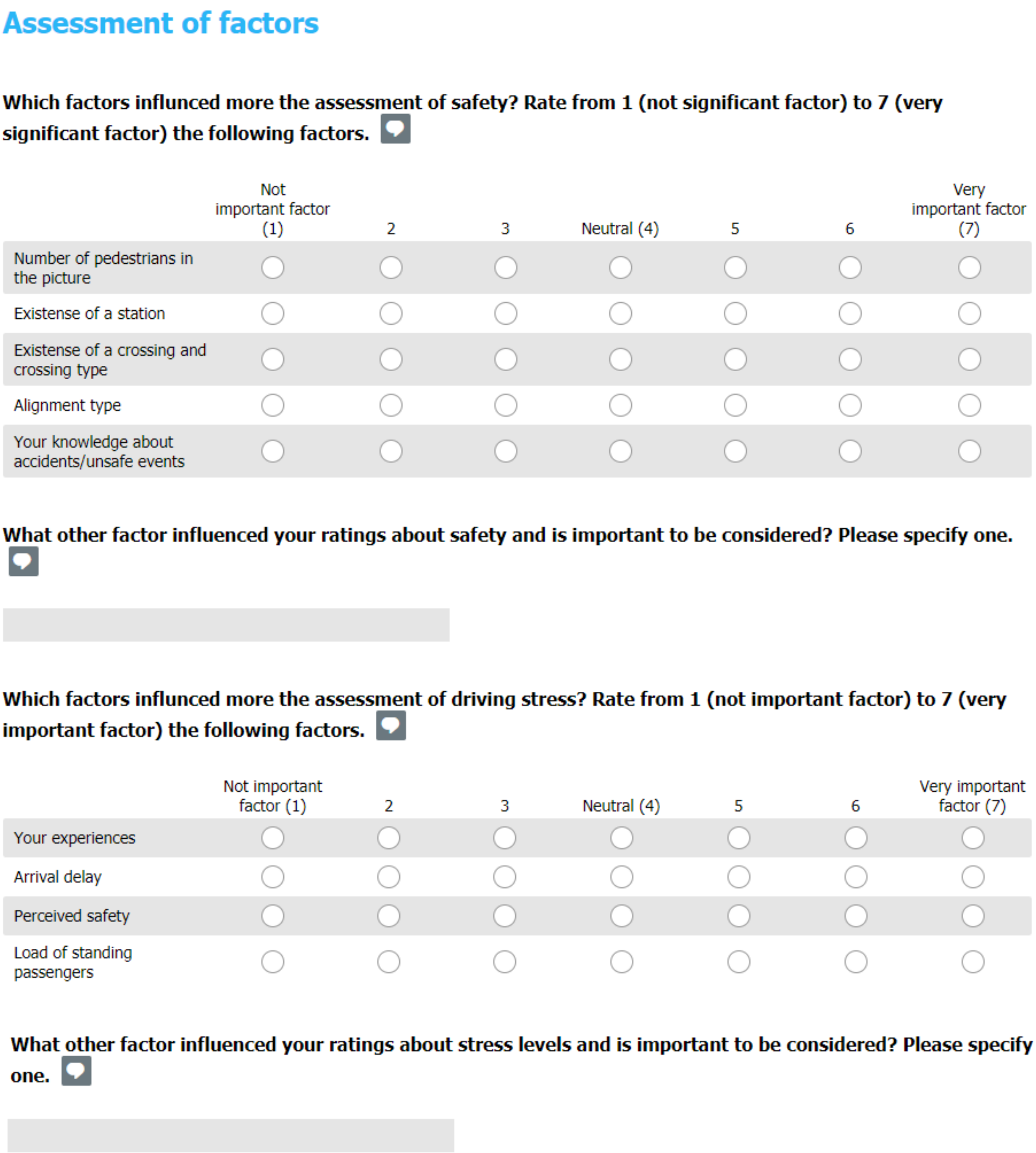
If, in the last driving conditions, you take into account that:

you are **5 minutes late** compared to the scheduled arrival time to the next station,
all seats are occupied and the number of **standing passengers** is **72** (50% less than the tram standing capacity).

Rate from 1 (not stressful at all) to 7 (very stressful) the level of driving stress, you would feel.

Not stressful at all (1)	2	3	Moderate stress (4)	5	6	Very stressful (7)
○	○	○	○	○	○	○

Figure A.14: Page 12 (b) of the online form



Assessment of factors

Which factors influnced more the assessment of safety? Rate from 1 (not significant factor) to 7 (very significant factor) the following factors.

	Not important factor (1)	2	3	Neutral (4)	5	6	Very important factor (7)
Number of pedestrians in the picture	○	○	○	○	○	○	○
Existense of a station	○	○	○	○	○	○	○
Existense of a crossing and crossing type	○	○	○	○	○	○	○
Alignment type	○	○	○	○	○	○	○
Your knowledge about accidents/unsafe events	○	○	○	○	○	○	○

What other factor influenced your ratings about safety and is important to be considered? Please specify one.

Which factors influnced more the assessment of driving stress? Rate from 1 (not important factor) to 7 (very important factor) the following factors.

	Not important factor (1)	2	3	Neutral (4)	5	6	Very important factor (7)
Your experiences	○	○	○	○	○	○	○
Arrival delay	○	○	○	○	○	○	○
Perceived safety	○	○	○	○	○	○	○
Load of standing passengers	○	○	○	○	○	○	○

What other factor influenced your ratings about stress levels and is important to be considered? Please specify one.

Figure A.15: Page 13 of the online form

Demographics

What is your gender?

- ◯ Female
- ◯ Male
- ◯ Prefer not to say

What is your age group?

- ◯ 20 or younger
- ◯ 21 to 30
- ◯ 31 to 40
- ◯ 41 to 50
- ◯ 51 to 60
- ◯ 60 or older
- ◯ Prefer not to say

How many years of tram driving experience do you have?

- ◯ Less than 3 years
- ◯ Between 3 to 15 years
- ◯ More than 15 years
- ◯ Prefer not to say

Figure A.16: Page 14 of the online form

B

Appendix: Online maps

One online map for the tram network of Athens and one online map for tram network of Amsterdam have been developed and uploaded on Google My Maps. The collected data and results of this thesis have been imported on these online maps, By observing these maps, the user can be informed about perceived safety as it was estimated in the tram network of Athens and about the location of the past tram-VRU accidents that have occurred in Amsterdam in the period 2007-2017.

B.1. Athens

The online map of the network of Athens can be found by clicking in the next link: Online map of the tram network of Athens: perceived safety.

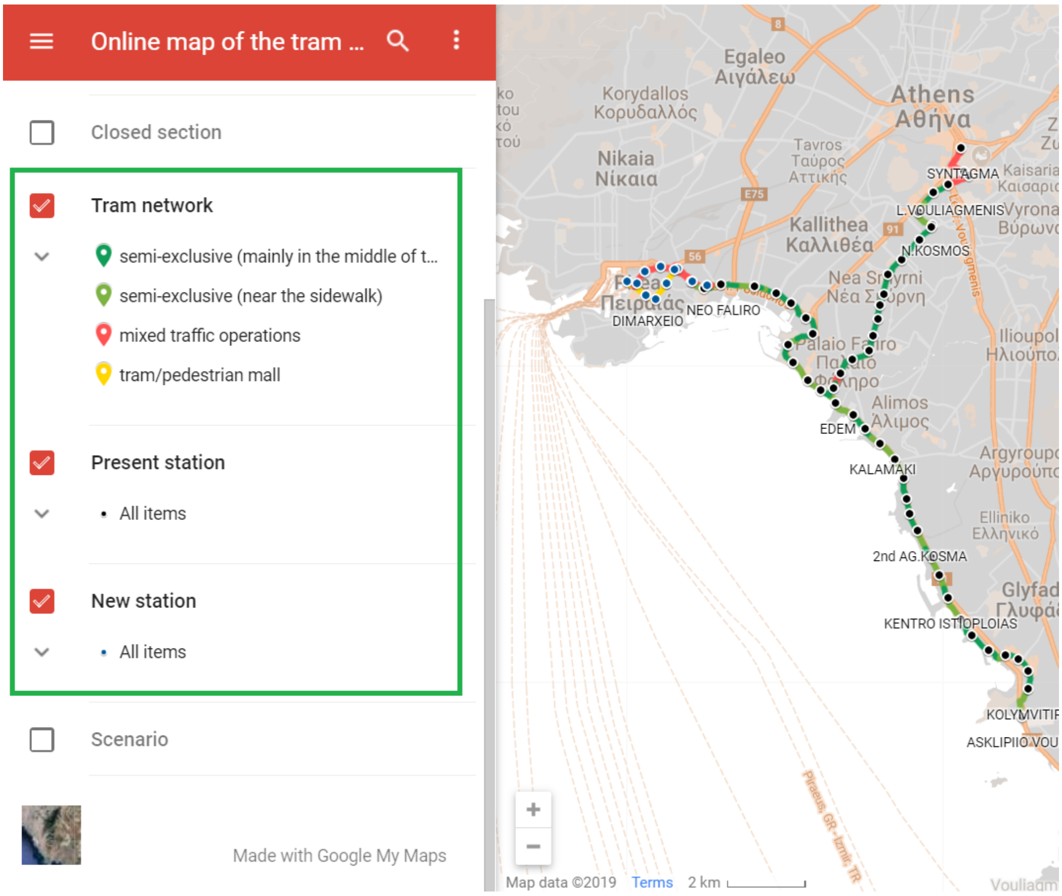


Figure B.1: Online map screenshot that shows the tram network of Athens and the locations of stations

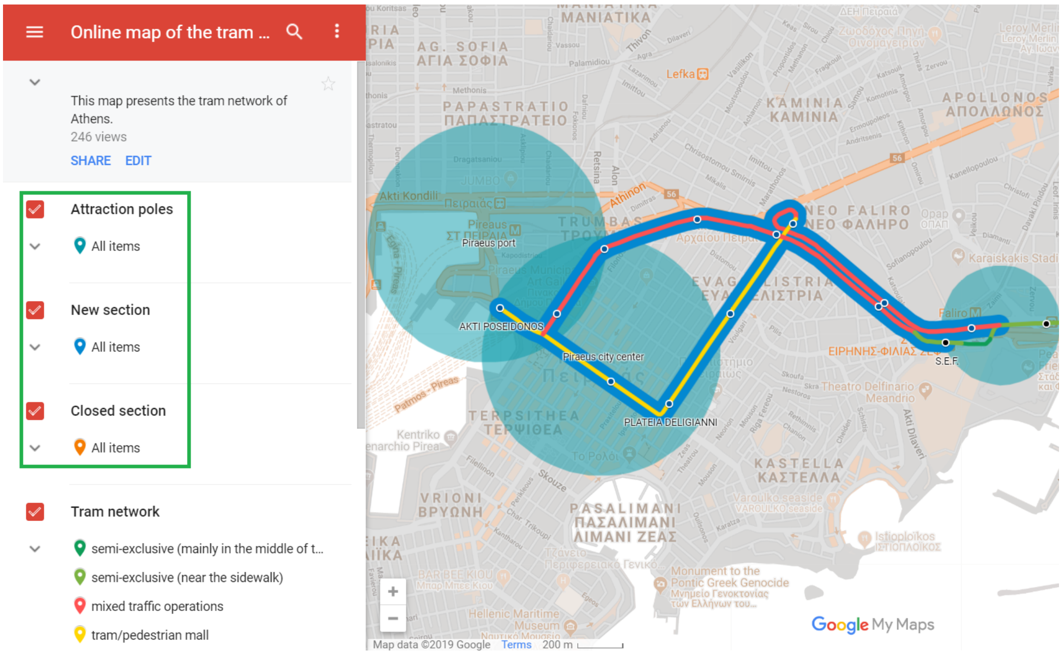


Figure B.2: Online map screenshot that shows the new tram section and some attraction poles

When the user opens the map, the layers with names ”tram network”, ”present stations” and ”new stations” are active. The tram network of Athens has been classified according to the alignment type. As it has been noted, four types of alignments were observed in this study network, namely: tram/pedestrian mall, mixed traffic operations, semi-exclusive alignment next to the sidewalk and semi-exclusive alignment located in the middle of the street. The layer ”new stations” contains the stations of the new tram section, which is located in Piraeus. Labels with their names written in Latin capital letters have been added on the online map of the tram network of Athens. All the previously described kml files were downloaded from www.stasy.gr. The classification of the network according to the alignment type of each section was conducted by the author of this thesis through the utilization of Google Earth satellite images and Google Earth StreetView images. Furthermore, the length of each segment of the network was estimated. Figure B.1 shows a screenshot of this online map.

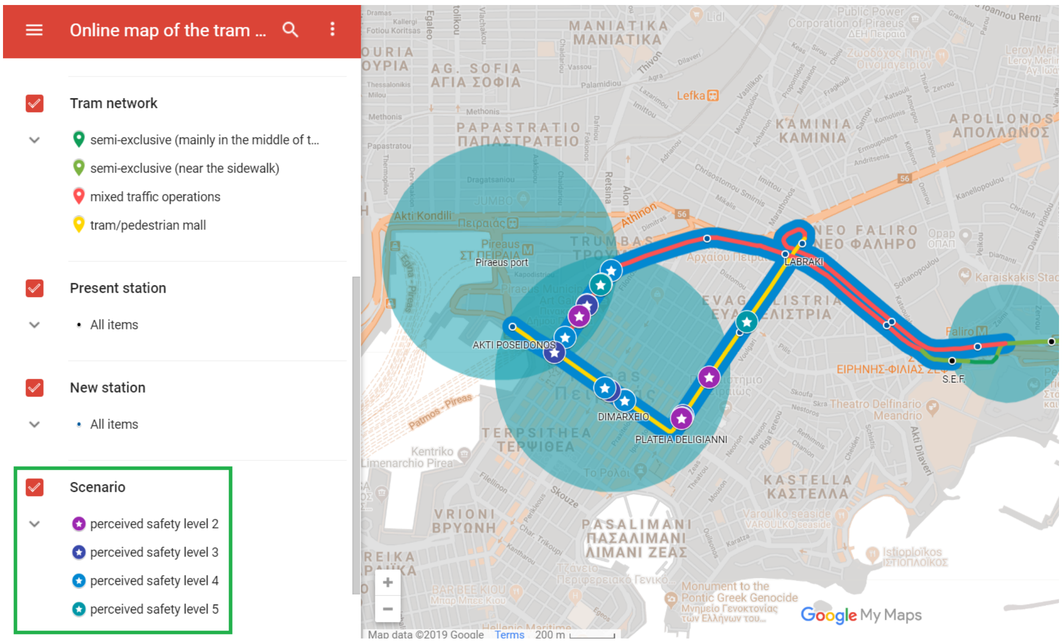


Figure B.3: Online map screenshot that shows the locations of all scenarios

By activating the "new section" and "closed section" layers, the locations of the new and closed section of the tram network of Athens are shown in the online map. As it has been mentioned, in both sections, the operations may start in December 2019. Another interesting layer is the one that gives the location of the attraction poles that are next to the tram network (see figure B.2). It is expected that the volume of pedestrians is quite high in the streets around attraction poles. These poles are: Piraeus port, Piraeus city center, Karaiskaki stadium-SEF, SNFCC, Flisvos marina, Alimos beach, Glifada center, Nea Smirni center, Neos Kosmos, Zappeio, Kallimarmaro, National Garden, Temple of Olympian Zeus and Syntagma. In order to generate zones of influence, the geoprocessing tool "buffer" was utilized. The radius of the buffer zones differ among the attraction points. By clicking on the circular zones, the user can be informed about the size of the radius.

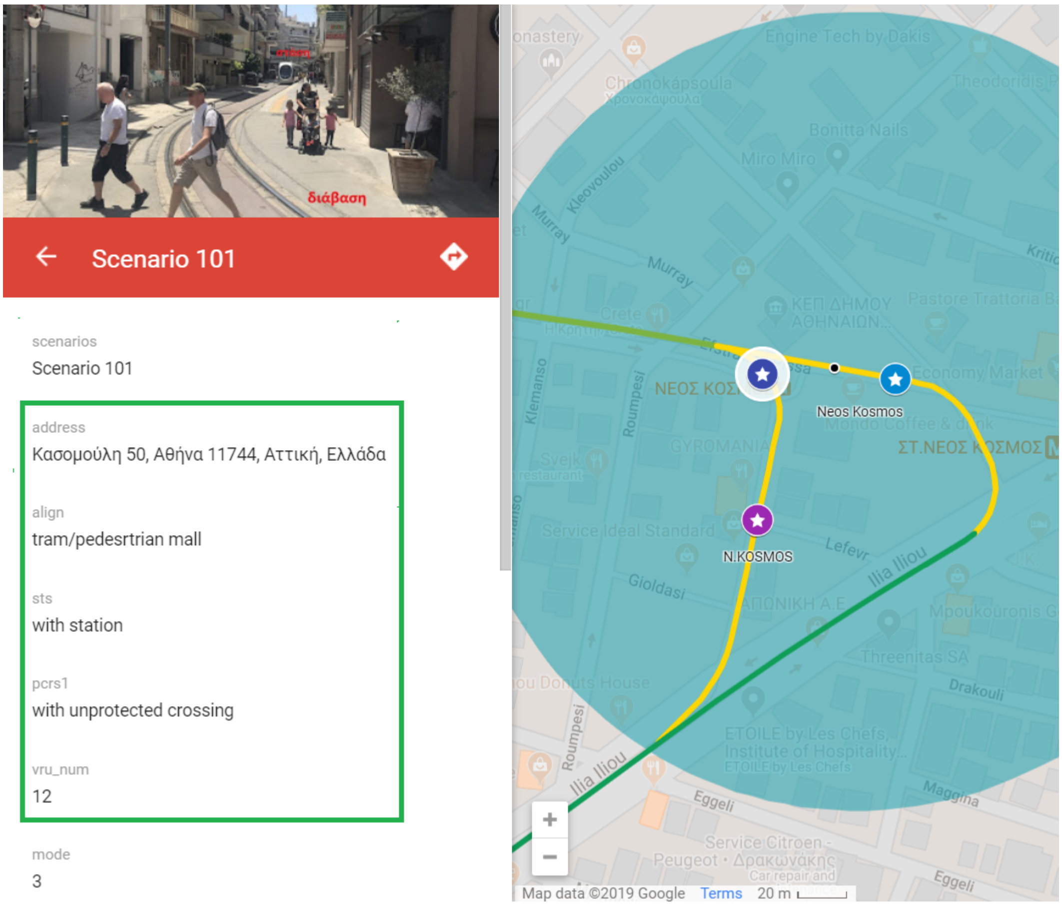


Figure B.4: Online map screenshot that shows the image and the characteristics of scenario 101

The locations of scenarios are presented by activating the layer called "scenario". The scenarios have been classified according to the perceived safety level as it was computed by the developed model using the mean betas. Different color has been used for each perceived safety level (see figure B.3). Also labels that give the scenario number have been added on the online map. By clicking on the scenario points (points with star), further details about each scenario are provided, as it can be seen in figure B.4. In the top-left side of the screen, the images that were used in the survey form are presented. The addresses are written in Greek Letters. The variable values of each scenario are presented in the information box. Descriptive statistics that were estimated using the ratings given by each tram driver of Athens are included in the information box, too (see figure B.5. Furthermore, the min and max perceived safety levels, as they were estimated by the developed model for a confidence interval of 95%, are reported there.

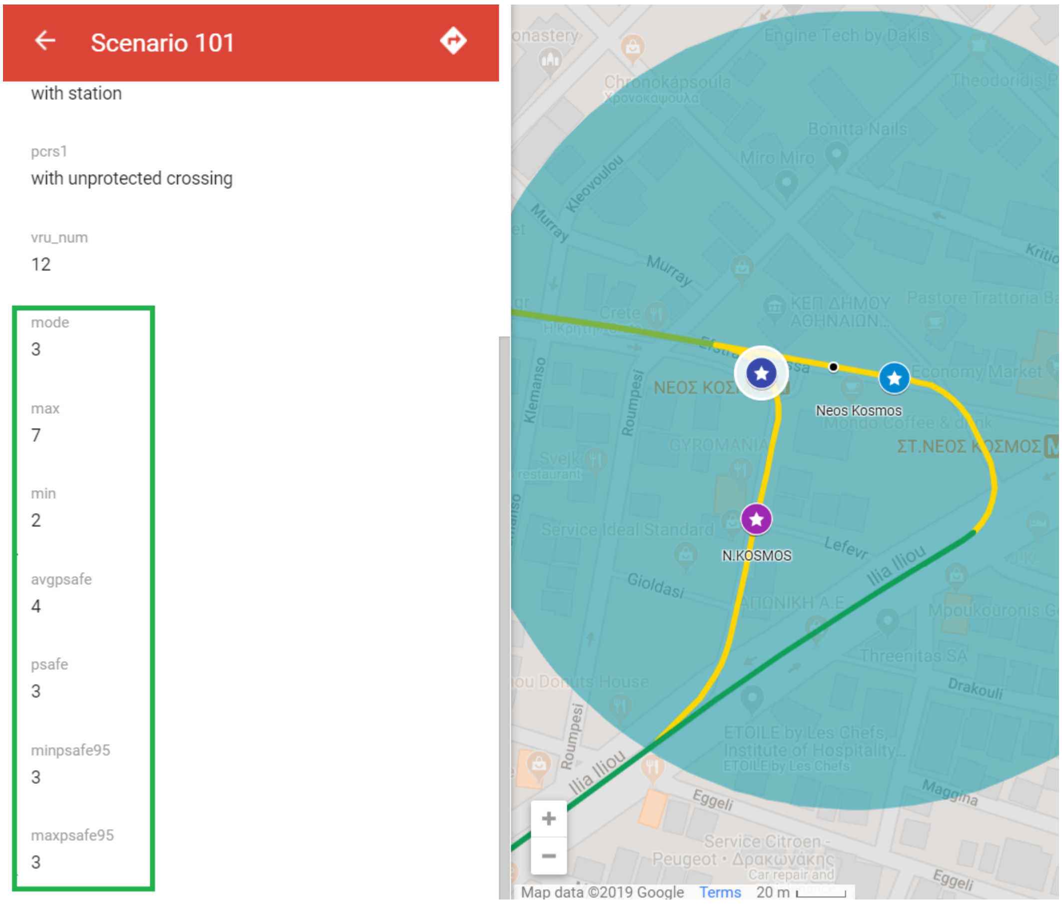


Figure B.5: Online map screenshot that shows perceived safety estimations

B.2. Amsterdam

The online map of the network of Amsterdam can be found by clicking in the next link: Online map of the tram network of Amsterdam: objective safety.

By default, the layers with names "tram network" and "tramstop" are active (see figure B.6). The tram network of Amsterdam has been classified by the author according to the alignment type. Four alignment types were observed in the tram network of Amsterdam, namely: tram/pedestrian mall, mixed traffic operation, semi-exclusive and exclusive alignment. By clicking in each segment, the user can be informed about its length. Also, the names of the tram stops are appeared in the map with labels. The data related with the tram network of Amsterdam was downloaded from `www.maps.amsterdam.nl`. The separation level of each segment was determined by looking at Google Earth satelite images and Google StreetView images.

In Amsterdam, the locations of the pedestrian and cycling crossings were mapped and added on the online map. The total number of crossings is equal to 590. By looking at Google SteetView images pf 2019, the crossings were categorized according to the protection level. Figure B.7 shows the location of pedestrian and cycling crossings in the tram network of Amsterdam

In order to find out the sections of the tram network of Amsterdam, where the volume of VRUs is quite high, the touristic attraction poles of Amsterdam were mapped (see figure B.8). These are: Amsterdam Central Station, Westermarkt, Damrak, Dam square, Rokin, Muntplein, Rembrandtplein, Waterplein, ARTIS, Leiderstraat, Leidseplein, Vondelpark and Museumplein. A circular buffer zone with radius equal to 150 m was created around each of them. Also labels with the name of the attraction poles were added. Furthermore it is well known that the (historical) center of Amsterdam (Centrum) is very crowded; therefore, many interactions between trams and VRUs may be observed inside it.

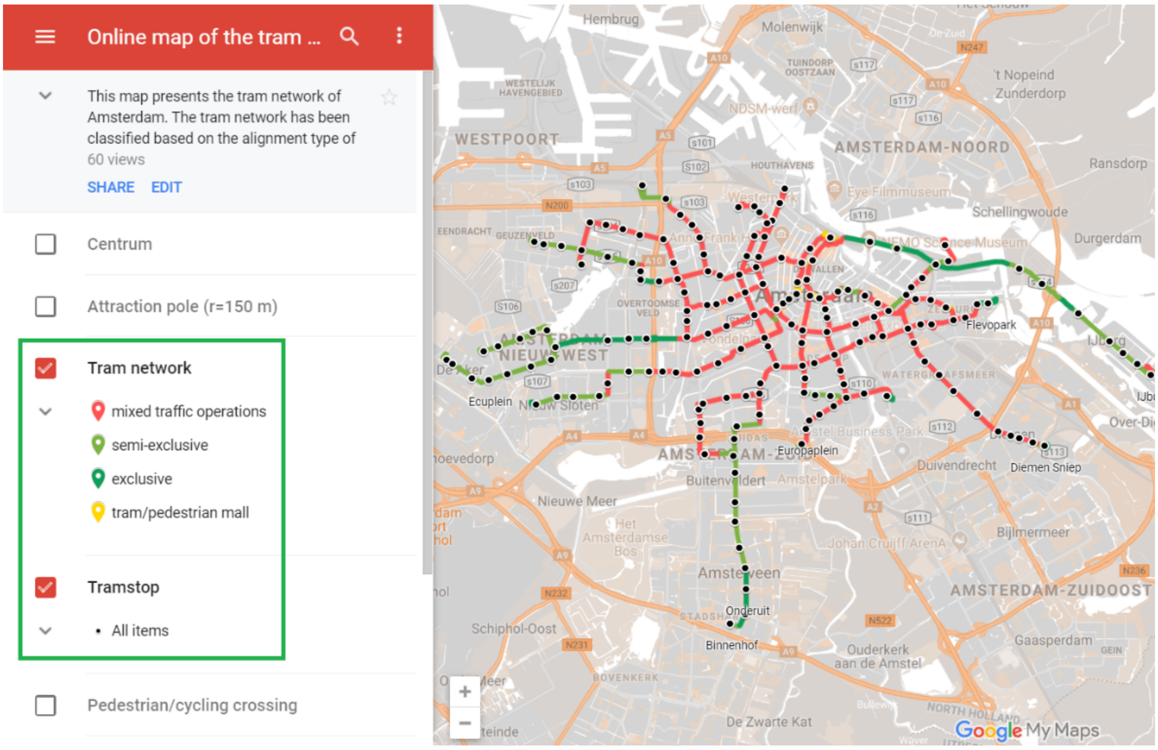


Figure B.6: Online map screenshot that shows the tram network of Amsterdam and the locations of tram stops

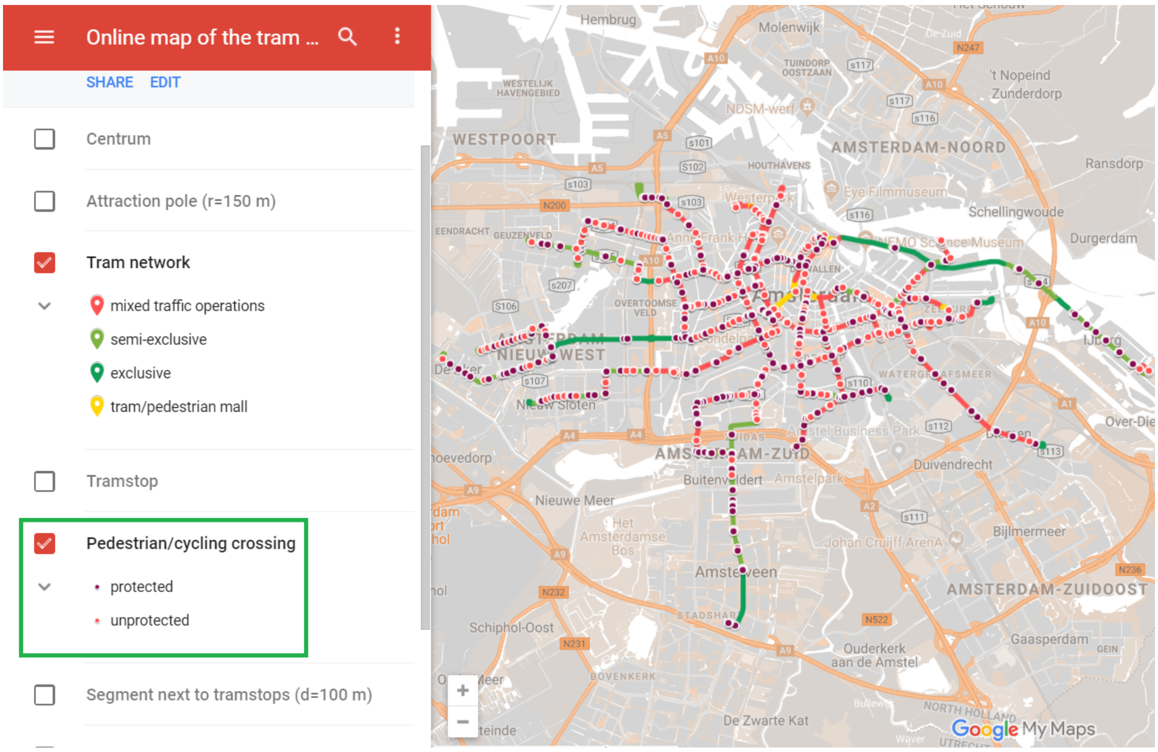


Figure B.7: Online map screenshot that shows the locations of pedestrian/cycling crossings

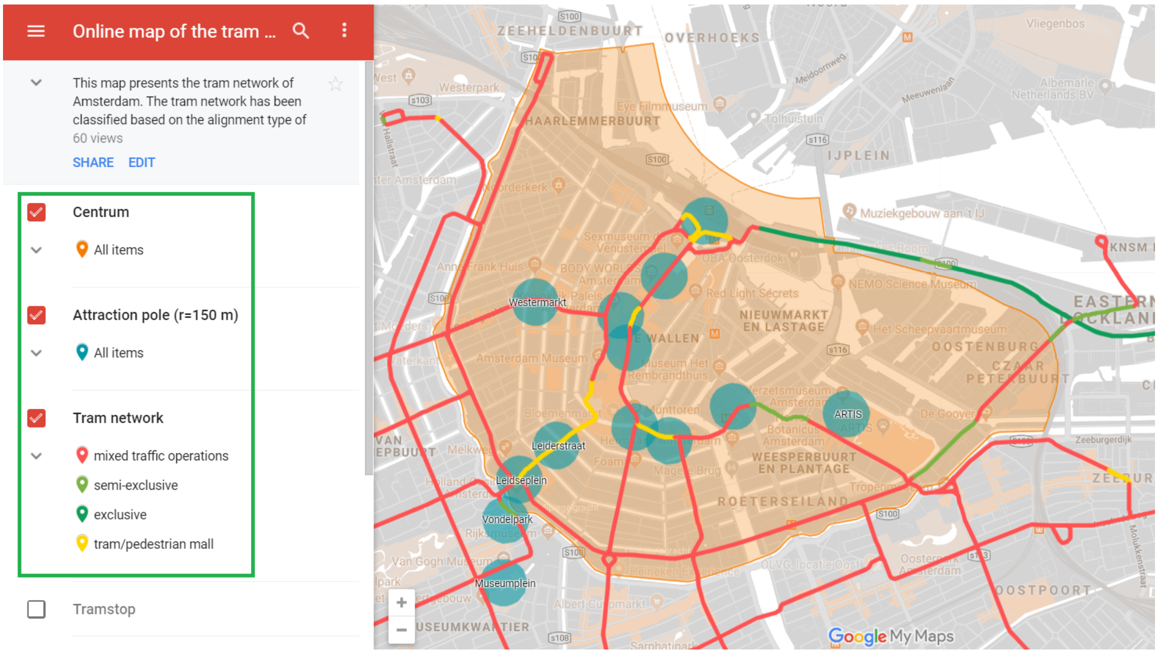


Figure B.8: Online map screenshot that shows the locations of attraction poles

Two additional layers that shows the segments next to tram stops and pedestrian/cycling crossings were imported on the online map (see figure B.9 and B.10). In order to identify them, buffer zones of 50 and 100 m around tram stops and crossings were created respectively. Segments that were inside the buffer zone were saved. The length of each segment is given in the information by clicking in one of them.

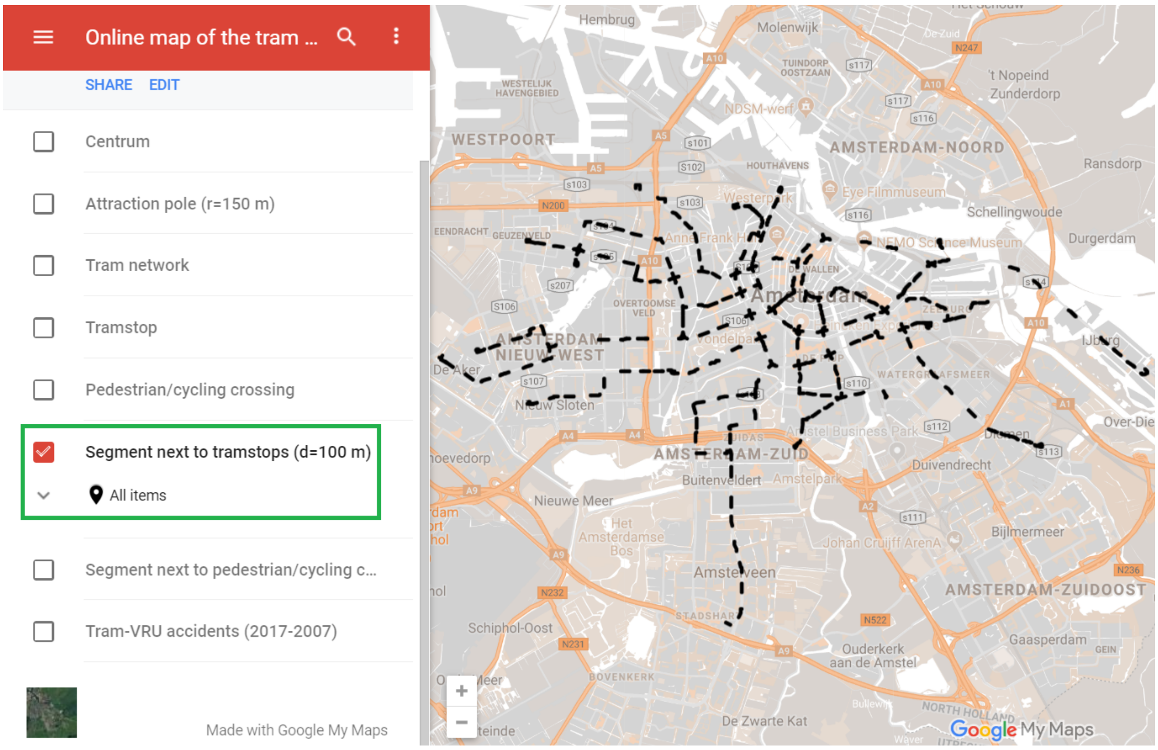


Figure B.9: Online map screenshot that shows segments next to tram stops

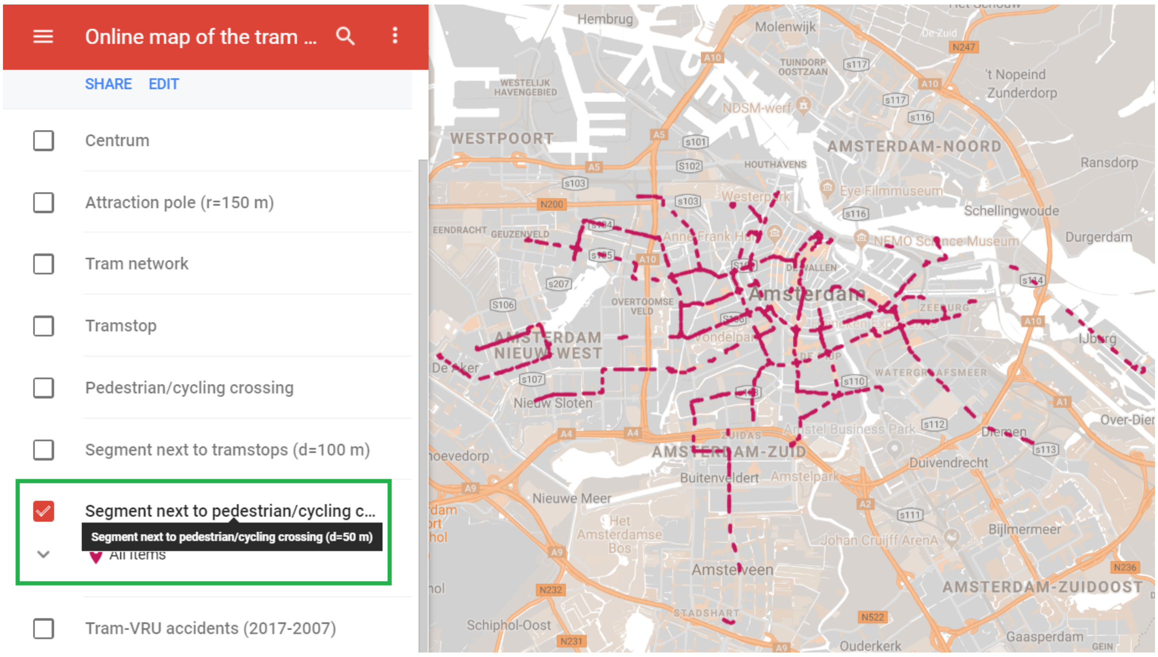


Figure B.10: Online map screenshot that shows segments next to pedestrian/cycling crossings

The locations of the tram-VRU accidents that occurred in the time period 2007-2017 in the tram network of Amsterdam are presented by activating the layer "accident". The crashes were categorized into different severity levels. Fatal accidents are presented with purple color, accidents with severe road injuries are shown with dark blue color and accidents with minor road injuries are shown with light blue color (see figure B.11). By clicking in the points with star, the user can see further details related with each crash (see figure B.12). Align1, align2 and align3 are dummy variables that show if one accident occurred in a tram/pedestrian mall, a mixed traffic operations section and a semi-exclusive alignment, respectively.

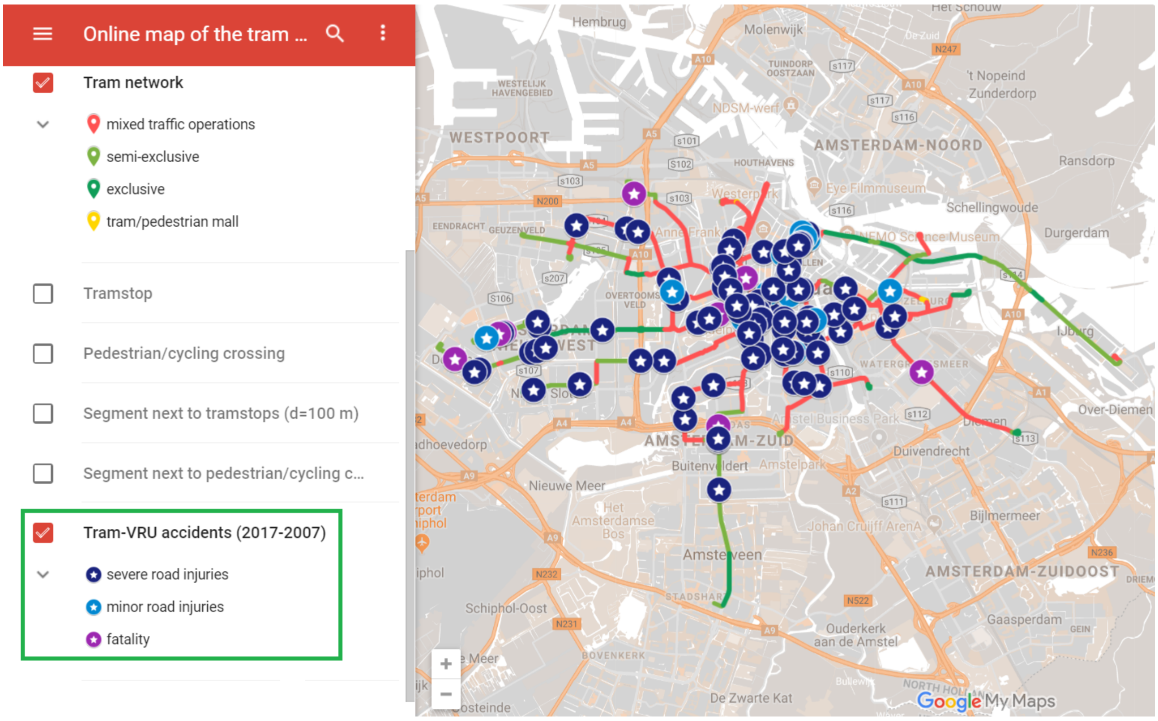


Figure B.11: Online map screenshot that shows the locations of past accidents

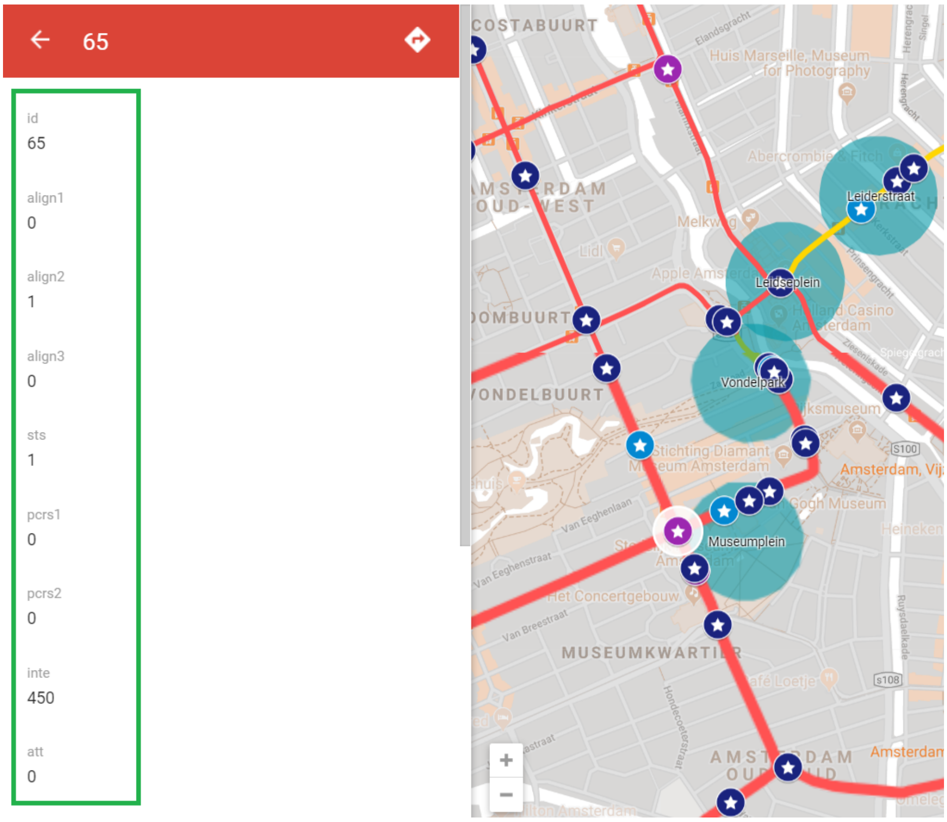


Figure B.12: Online map screenshot that shows information about accident 65 (1)

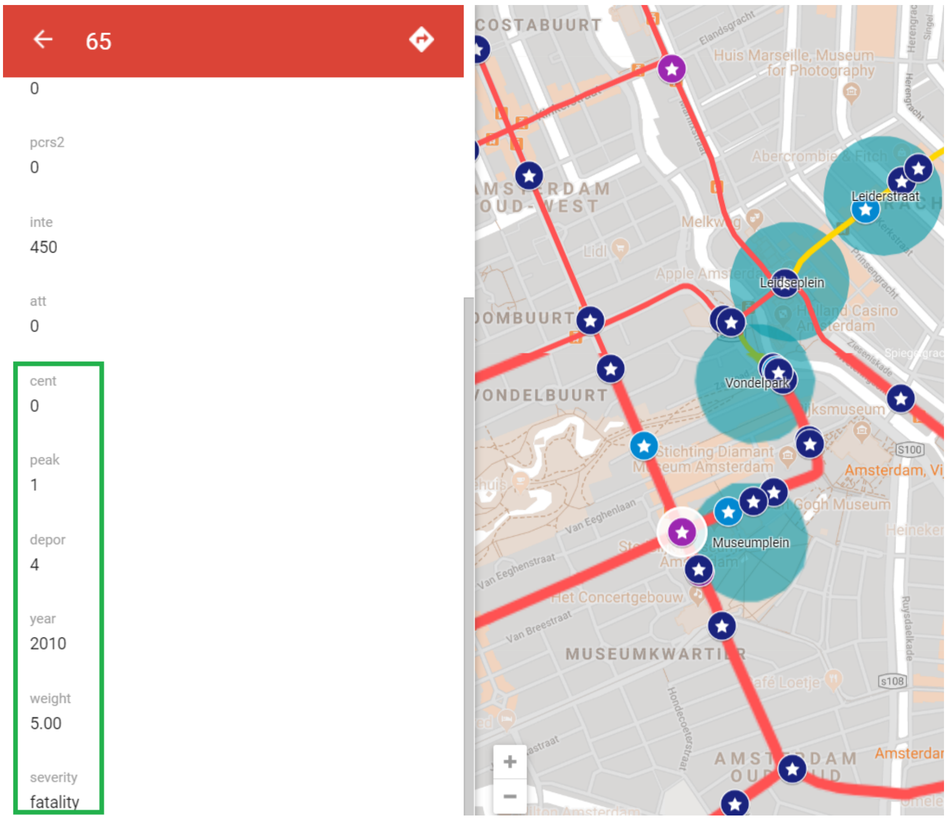


Figure B.13: Online map screenshot that shows information about accident 65 (2)

Pcrs1 is equal to 1 if there is no crossing near the accident location and pcrs2 is equal to 2 if there is an unprotected crossing next to the accident location. The inte variable shows the cycling intensity in cycle lanes next to the tram alignment. The cycling intensity was measured during the Dutch Bicycle Count Week in 2016. Also the values of both att and cent variables are equal to 1, when the location of the tram-VRU accident is next to an attraction pole which is inside the Centrum (e.g. Dam square). The peak dummy variable is equal to 1 if the crash has been occurred during peak hours. Depor is a categorized variable; its value is equal to 4, 3 and 2, when the outcome of the crash is a fatality or a severe road injury or s minor road injury, respectively. The year when the accident happened is given in the information box (see figure B.13). Lastly the weights used in the black spot analysis are presented in the same box, too. Unfortunately the kml files from black spot analysis could not be uploaded on Google My Maps, since their sizes were bigger than 5 Mb.

C

Appendix: Models development

In the Results chapter, two models, i.e. one about perceived safety and one about driving stress, were presented. These models were selected as the best ones in statistical terms. For the computation of these final models, many different model forms were tested. Different datasets were used in this process; one of these datasets came from the pilot study. In addition, the proportional odds test was conducted in order to ensure that ordered logit is the appropriate method to estimate these ordinal models using the ratings from the survey. The computation process was executed in R Software by utilizing the statistical package ”Rchoice” developed by Sarrias (2016)

C.1. Pilot Study

A simple linear regression was run in order to estimate the perceived safety and driving stress models. In the pilot study, the number of respondents was very limited, i.e. equal to 4 trainers of STASY. Yet, the observations were enough to estimate a statistical model, since each respondent rated 14 times perceived safety and 12 times the driving stress.

	Estimate	Std. Error	P(>|z|)
constant	5.464	0.727	0.000
align1	-1.064	0.900	0.243
align2	-0.071	0.765	0.926
align3	0.164	0.981	0.868
pcrs1	-0.429	0.751	0.571
pcrs2	-0.627	0.641	0.333
sts	-0.374	0.898	0.679
vru_num	-0.079	0.059	0.190
Number of observations	56		
Degrees of freedom	48		
Multiple R	0.249		
Adjusted R Square	0.142		
Standard Error	1.791		
F-statistic	2.320		0.040

Table C.1: Linear regression model of perceived safety (pilot study)

The estimates of perceived safety models gave some hints regarding which beta parameters would be proved statistically significant in the next steps. The parameter connected with the volume of VRUs (vru_num) and the one connected with the existence of a tram track shared with pedestrians (align1) are typical examples (see table C.1). The adjusted R square was computed to be equal to 0.142. On the other hand, the estimates of driving stress model revealed the subjective nature of this notion. As it can be seen in table C.2, the multiple R was estimated to be equal to 0.018. After the completion of the pilot study, it was clear that it is very difficult to develop a driving stress model by conducting a stated preference survey. By taking into account the results of the driving stress model, some phrases in the question about it (second questions) were changed.

	Estimate	**Std. Error**	**P(>|z|)**
constant	2.030	1.162	0.088
psafe	0.051	0.165	0.761
time1	-0.019	0.033	0.575
load	0.419	0.754	0.581
Number of observations	48		
Degrees of freedom	44		
Multiple R	0.018		
Adjusted R Square	-0.048		
Standard Error	1.385		
F-statistic	0.282		0.839

Table C.2: Linear regression model of driving stress (pilot study)

C.2. Proportional odds test

A X^2 test was performed to test if the proportional odds assumption is valid in the estimation of perceived safety model and driving stress model using the dataset obtained from the survey. In practice, this test compares two different model forms; in the first form, the beta parameters are the same and unique for all the intervals, in the second form (with proportional odds assumption), the betas differ among the intervals (without proportional odds assumption).

```
Tests for Proportional Odds
polr(formula = psafe ~ align1 + align2 + align3 + pcrs1 + pcrs2 +
    vru_num, data = psafe_data4)

        b[polr]   b[>1]   b[>2]   b[>3]   b[>4]   b[>5]   b[>6] Chisquare df Pr(>Chisq)
Overall                                                           34.21 30       0.27
align1  -1.0519 -0.4247 -0.7966 -0.7394 -1.0565 -1.6965 -2.1273      6.83  5       0.23
align2  -1.1010 -0.9103 -0.9607 -0.9632 -0.8862 -1.0046 -1.2057      0.50  5       0.99
align3  -0.4092  0.1163 -0.1035 -0.3619 -0.5647 -0.3624 -0.2073      2.81  5       0.73
pcrs1   -0.5320 -0.7157 -0.7874 -0.8204 -0.4198 -0.2140 -0.5436      4.27  5       0.51
pcrs2   -0.8322 -1.4697 -1.3547 -1.0492 -0.8315 -0.3098 -0.7517      8.89  5       0.11
vru_num -0.0860 -0.1008 -0.0918 -0.0796 -0.0738 -0.0975 -0.1027      5.84  5       0.32
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Figure C.1: Output from proportional odds test (perceived safety model)

As it can be seen in figure C.1, for a relatively small confidence interval of almost 73%, the perceived safety model without the proportional odds assumption represents better the population. Hence the X^2 is not statistically significant for a confidence interval of 95%, so null hypothesis (i.e. valid proportional odds assumption) cannot be rejected. The null hypothesis is also valid in the estimation of the driving stress model. For a relatively small confidence interval of almost 63%, the driving stress model without the proportional odds assumptions represents better the population (see figure C.2). At this point, it should be noted that only the statically significant betas of both ordered logit models were introduced in this test.

```
Tests for Proportional Odds
polr(formula = stress ~ time1 + load + fam, data = stress_data)

        b[polr]   b[>1]   b[>2]   b[>3]   b[>4]   b[>5]   b[>6] Chisquare df Pr(>Chisq)
Overall                                                             16.21 15       0.37
time1    0.0524  0.0559  0.0539  0.0509  0.0579  0.0636  0.0470      3.50  5       0.36
load     0.4022  0.1293  0.4409  0.2199  0.5031  0.3618  0.3233      7.75  5       0.17
fam     -0.1932 -0.2439 -0.2409 -0.2716 -0.1330 -0.2880  0.0337      3.91  5       0.56
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Figure C.2: Output from proportional odds test (driving stress model)

C.3. Perceived Safety

To estimate the perceived safety model, the primary idea was to introduce all the independent variables, which are presented in table 5.2, in the model function in order to see which variables are significant and which are not. Personal characteristics included in the function of model100_psafe; therefore, the dataset (psafe_data2) that was imported contained only ratings from respondents who answered all the demographic questions (i.e. gender + age + experience). In the beginning, none of the variables was selected to be random. In the estimation process, individuals were distinguished according to their id (panel data). Figure C.3 presents the output extracted from the estimation of model100_psafe.

As it can be seen, age and experience are statistically significant for a 95% confidence interval. Age is insignificant, since it is partly correlated with experience. The dummy variables related with the alignment type are not statistically significant for the same confidence interval. On the contrary, familiarity, the existence of an unprotected crossing and the volume of VRUs affected the choices of tram drivers. The sign of the parameter that corresponds to the existence of a station is positive; this means that areas around stations are (subjectively) safer than areas away from. The number of observations that were utilized for the estimation of this model were 448 and the maximum value of the loglikelihood was estimated to be equal to -775.2.

Next step is to test if age instead of experience and gender impacts on perceived safety. As it was shown in figure 6.1, the variance observed in ages of tram drivers is higher compared to the other independent variables about personal characteristics. Figure C.4 shows the output from the estimation process of model101_psafe. Age seems to be unrelated with perceived safety. Furthermore, the maximum value of the loglikelihood is lower compared to previously estimated model.

In the estimation of model102_psafe, the independent variables about personal characteristics were excluded and the full dataset (psafe_data) that contains 672 observations was imported. From the beginning, the objective of this analysis was to examine the fluctuation of perceived safety in different road environments. Observations about personal characteristics had a very low variance. In addition, not all the respondents answered the questions about their gender, age and experience; thus, the sample size was reduced by 224 observations. Factors related with familiarity, volume of VRUs and existence of unprotected crossing were estimated statistically significant for a 95% confidence interval (see figure C.5). Also, sections without pedestrian crossings are unsafer in comparison with sections with protected crossings, according to the views of tram drivers. The parameters related with the alignment type are estimated insignificant in model102_psafe. The maximum value of the loglikelihood was calculated to be equal to -1165.

Familiarity is correlated with align1 and align2 parameters. Many unfamiliar sections are located in Piraeus, where the tram line is shared either with pedestrians (i.e. align1 equal to 1) or with the motorized traffic (i.e. align2 equal to 1). Also, in the analysis that is presented in the sub-chapter 6.1.3, the contribution of familiarity to perceived safety is not significant if all the other variables remain stable. Therefore, the previous estimates of the familiarity parameter only show that non-exclusive alignments downgrade perceived safety. In model103_psafe, the factor of familiarity is discarded from the model function. In addition, the factors related with the alignment type are selected to be random, so that heterogeneity in ”tastes” among the individuals can be reported. It was assumed that the random beta parameters follow a normal distribution. The simulation was chosen to be based on 100 Halton draws.

As it can be seen in the results presented in figure C.6, the means and the standard deviations of the factors about alignment type are statistically significant for a 99% confidence interval. One exception to this is the meam.align3 parameter. This means that there is no significant difference for a 95% confidence interval between a semi-exclusive alignment located next to the sidewalk and a semi-exclusive one located in the middle of the street. The factors, which are connected with the existence of a station and the non-existence of a crossing in the next 50 m of the tram line, are statically significant for a 95% confidence interval and statistically insignificant for a 99% confidence interval. The maximum value of the loglikelihood was estimated to be equal to -1130. By performing a X^2 test, it can be concluded that model103_psafe represents better the population in comparison with model102_psafe that contains the familiarity parameter in the model function.

Another option was to increase the number of Halton draws to 2000 and choose all the independent variables of the previous model to be random. As it can be observed in figure C.7, the many of the standard deviations are statically significant for a 99% confidence interval. The standard deviations of align2 and align3 parameters were estimated statically insignificant for a 95% confidence interval. This means that the previously mentioned parameters are not random, since the heterogeneity among the individuals is relatively small. The maximum value of the loglikelihood was increased by 53. By performing a X^2 test, for a 99% confidence interval, it can be concluded that the model104_psafe represents better the population than all the other previously described models.

The full dataset (i.e. psafe_data) contained correlations among independent variable, since two additional scenarios (i.e. scenarios 101, 108, 115, 125, 126 and 136) had been added in each block of questions so that the contribution of familiarity to perceived safety could be examined. The existence of correlations influenced negatively the statically significance of the beta parameters in all the previously presented models, because the full dataset contains more scenarios with non-exclusive alignments and unprotected crossings and less scenarios with semi-exclusive alignments. The size of the dataset (i.e. psafe_data4) without correlations is smaller by 96 observations compared to the full dataset (i,e, psafe_data). The output of the model105_psafe is presented in figure C.8. It is clear that the z values of all beta parameters were increased. Now, the standard deviation of align2 parameter is statistically significant for 99% confidence interval. The mean values of the factors connected with the existence of a tram track next to the sidewalk and the existence of a station are statistical insignificant for a 90% confidence interval. The maximum value of the loglikelihood was estimated to be equal to -904.2.

The final model of perceived safety can be estimated by discarding the beta parameters that were statically insignificant in the previous model, namely align3 and sts. The output of the model106_psafe is presented in figure C.9. All the parameters are now statistically significant for a 95% confidence interval. All of them have been correctly selected to be random. The existence of random parameters proves the subjective nature of perceived safety. Lastly, the contribution of the familiarity and personal characteristics to perceived safety can be described by the heterogeneity in ”tastes” among the individuals.

```
Frequencies of categories:
y
      1       2       3       4       5       6       7
0.09598 0.15402 0.18080 0.27232 0.12723 0.10938 0.06027
The estimation took: 0h:0m:0s

Coefficients:
          Estimate Std. Error z-value Pr(>|z|)
kappa.1   1.317902   0.150542   8.754  < 2e-16 ***
kappa.2   2.293864   0.174592  13.138  < 2e-16 ***
kappa.3   3.609277   0.199212  18.118  < 2e-16 ***
kappa.4   4.417364   0.218210  20.244  < 2e-16 ***
kappa.5   5.668397   0.272454  20.805  < 2e-16 ***
constant  3.980053   0.813810   4.891 1.01e-06 ***
gender   -0.977607   0.298507  -3.275 0.001057 **
age       0.003663   0.016312   0.225 0.822304
expe      0.846885   0.221706   3.820 0.000134 ***
align1   -0.529080   0.323976  -1.633 0.102451
align2   -0.499256   0.327278  -1.525 0.127139
align3   -0.361929   0.263777  -1.372 0.170031
sts      -0.465091   0.185204  -2.511 0.012031 *
pcrs1    -0.552328   0.218211  -2.531 0.011368 *
pcrs2    -0.735342   0.222131  -3.310 0.000932 ***
vru_num  -0.065926   0.009474  -6.959 3.44e-12 ***
fam       0.537406   0.273468   1.965 0.049397 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Optimization of log-likelihood by BFGS maximization
Log Likelihood: -775.2
Number of observations: 448
Number of iterations: 94
Exit of MLE: successful convergence
```

Figure C.3: Output from the computation of model100_psafe

```
Frequencies of categories:
y
      1       2       3       4       5       6       7
0.09598 0.15402 0.18080 0.27232 0.12723 0.10938 0.06027
The estimation took: 0h:0m:0s

Coefficients:
          Estimate Std. Error z-value Pr(>|z|)
kappa.1   1.271739   0.145662   8.731  < 2e-16 ***
kappa.2   2.219631   0.169173  13.120  < 2e-16 ***
kappa.3   3.502946   0.192797  18.169  < 2e-16 ***
kappa.4   4.288261   0.211043  20.319  < 2e-16 ***
kappa.5   5.509502   0.265058  20.786  < 2e-16 ***
constant  3.787725   0.777687   4.871 1.11e-06 ***
age       0.006242   0.015716   0.397  0.69125
align1   -0.517951   0.323572  -1.601  0.10944
align2   -0.459796   0.325580  -1.412  0.15788
align3   -0.408978   0.261292  -1.565  0.11753
sts      -0.414462   0.184252  -2.249  0.02449 *
pcrs1    -0.507329   0.218227  -2.325  0.02008 *
pcrs2    -0.718525   0.220347  -3.261  0.00111 **
vru_num  -0.063655   0.009439  -6.744 1.54e-11 ***
fam       0.526816   0.274058   1.922  0.05457 .
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Optimization of log-likelihood by BFGS maximization
Log Likelihood: -787
Number of observations: 448
Number of iterations: 80
Exit of MLE: successful convergence
```

Figure C.4: Output from the computation of model101_psafe

```
Frequencies of categories:
y
      1       2       3       4       5       6       7
0.08929 0.14137 0.17560 0.28274 0.14881 0.09970 0.06250
The estimation took: 0h:0m:0s

Coefficients:
          Estimate Std. Error z-value Pr(>|z|)
kappa.1   1.258409   0.122864  10.242  < 2e-16 ***
kappa.2   2.223219   0.142616  15.589  < 2e-16 ***
kappa.3   3.569473   0.162457  21.972  < 2e-16 ***
kappa.4   4.495361   0.179650  25.023  < 2e-16 ***
kappa.5   5.626253   0.219424  25.641  < 2e-16 ***
constant  4.055965   0.336509  12.053  < 2e-16 ***
align1   -0.257920   0.263506  -0.979  0.32768
align2   -0.279020   0.268348  -1.040  0.29845
align3   -0.307255   0.218777  -1.404  0.16019
sts      -0.289229   0.151440  -1.910  0.05615 .
pcrs1    -0.488665   0.177027  -2.760  0.00577 **
pcrs2    -0.896505   0.181033  -4.952 7.34e-07 ***
vru_num  -0.073627   0.007611  -9.674  < 2e-16 ***
fam       0.713165   0.222299   3.208  0.00134 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Optimization of log-likelihood by BFGS maximization
Log Likelihood: -1165
Number of observations: 672
Number of iterations: 75
Exit of MLE: successful convergence
```

Figure C.5: Output from the computation of model102_psafe

```
Frequencies of categories:
y
      1       2       3       4       5       6       7
0.08929 0.14137 0.17560 0.28274 0.14881 0.09970 0.06250
The estimation took: 0h:0m:14s

Coefficients:
             Estimate Std. Error z-value Pr(>|z|)
kappa.1      1.513359   0.148044  10.222  < 2e-16 ***
kappa.2      2.695096   0.176251  15.291  < 2e-16 ***
kappa.3      4.342242   0.210122  20.665  < 2e-16 ***
kappa.4      5.452099   0.236524  23.051  < 2e-16 ***
kappa.5      6.730540   0.279845  24.051  < 2e-16 ***
constant     5.673394   0.334012  16.986  < 2e-16 ***
sts         -0.370614   0.157705  -2.350 0.018771 *
pcrs1       -0.448656   0.184196  -2.436 0.014861 *
pcrs2       -0.904402   0.182617  -4.952 7.33e-07 ***
vru_num     -0.088642   0.008611 -10.295  < 2e-16 ***
mean.align1 -1.004022   0.277322  -3.620 0.000294 ***
mean.align2 -1.126157   0.284591  -3.957 7.59e-05 ***
mean.align3 -0.458511   0.283737  -1.616 0.106100
sd.align1    1.375052   0.228902   6.007 1.89e-09 ***
sd.align2    1.307248   0.177366   7.370 1.70e-13 ***
sd.align3    1.181263   0.241063   4.900 9.57e-07 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Optimization of log-likelihood by BFGS maximization
Log Likelihood: -1130
Number of observations: 672
Number of iterations: 100
Exit of MLE: successful convergence
Simulation based on 100 Halton draws
```

Figure C.6: Output from the computation of model103_psafe

```
Frequencies of categories:
y
      1       2       3       4       5       6       7
0.08929 0.14137 0.17560 0.28274 0.14881 0.09970 0.06250
The estimation took: 0h:4m:48s

Coefficients:
             Estimate Std. Error z-value Pr(>|z|)
kappa.1       1.96731    0.19490  10.094  < 2e-16 ***
kappa.2       3.43792    0.23641  14.542  < 2e-16 ***
kappa.3       5.44956    0.29524  18.458  < 2e-16 ***
kappa.4       6.75674    0.33641  20.085  < 2e-16 ***
kappa.5       8.17530    0.38811  21.064  < 2e-16 ***
constant      6.88070    0.40770  16.877  < 2e-16 ***
mean.align1  -1.07235    0.25947  -4.133 3.58e-05 ***
mean.align2  -1.12884    0.24739  -4.563 5.04e-06 ***
mean.align3  -0.28918    0.25979  -1.113 0.265649
mean.sts     -0.10069    0.22839  -0.441 0.659308
mean.pcrs1   -0.60557    0.24081  -2.515 0.011911 *
mean.pcrs2   -1.30814    0.26842  -4.873 1.10e-06 ***
mean.vru_num -0.10963    0.01384  -7.919 2.44e-15 ***
sd.align1     0.88193    0.23590   3.739 0.000185 ***
sd.align2     0.55596    0.36675   1.516 0.129542
sd.align3     0.57241    0.31590   1.812 0.069987 .
sd.sts        0.92961    0.21774   4.269 1.96e-05 ***
sd.pcrs1      1.06967    0.22210   4.816 1.46e-06 ***
sd.pcrs2      1.44126    0.23568   6.115 9.64e-10 ***
sd.vru_num    0.07888    0.01074   7.345 2.06e-13 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Optimization of log-likelihood by BFGS maximization
Log Likelihood: -1069
Number of observations: 672
Number of iterations: 116
Exit of MLE: successful convergence
Simulation based on 2000 Halton draws
```

Figure C.7: Output from the computation of model104_psafe

```
Frequencies of categories:
y
      1       2       3       4       5       6       7
0.09722 0.14583 0.15972 0.28819 0.14410 0.09896 0.06597
The estimation took: 0h:3m:57s

Coefficients:
              Estimate Std. Error z-value  Pr(>|z|)
kappa.1        2.24895    0.25084   8.966  < 2e-16 ***
kappa.2        3.71139    0.30734  12.076  < 2e-16 ***
kappa.3        5.86257    0.39070  15.005  < 2e-16 ***
kappa.4        7.17249    0.44381  16.161  < 2e-16 ***
kappa.5        8.59767    0.50689  16.962  < 2e-16 ***
constant       7.64710    0.54610  14.003  < 2e-16 ***
mean.align1   -1.70805    0.30127  -5.669 1.43e-08 ***
mean.align2   -1.51747    0.28370  -5.349 8.85e-08 ***
mean.align3   -0.41756    0.27853  -1.499  0.13384
mean.sts       0.27225    0.20398   1.335  0.18197
mean.pcrs1    -0.74438    0.27556  -2.701  0.00691 **
mean.pcrs2    -1.68492    0.33367  -5.050 4.43e-07 ***
mean.vru_num  -0.13904    0.01706  -8.150 4.44e-16 ***
sd.align1      0.84506    0.33378   2.532  0.01135 *
sd.align2      0.82789    0.31419   2.635  0.00841 **
sd.align3      0.81953    0.29289   2.798  0.00514 **
sd.sts         0.50972    0.44391   1.148  0.25087
sd.pcrs1       1.29044    0.24892   5.184 2.17e-07 ***
sd.pcrs2       1.66024    0.28269   5.873 4.28e-09 ***
sd.vru_num     0.08819    0.01388   6.352 2.12e-10 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Optimization of log-likelihood by BFGS maximization
Log Likelihood: -904.2
Number of observations: 576
Number of iterations: 112
Exit of MLE: successful convergence
Simulation based on 2000 Halton draws
```

Figure C.8: Output from the computation of model105_psafe

```
Frequencies of categories:
y
      1       2       3       4       5       6       7
0.09722 0.14583 0.15972 0.28819 0.14410 0.09896 0.06597
The estimation took: 0h:2m:56s

Coefficients:
             Estimate Std. Error z-value Pr(>|z|)
kappa.1       2.18217    0.23369   9.338  < 2e-16 ***
kappa.2       3.59305    0.27637  13.001  < 2e-16 ***
kappa.3       5.64331    0.33609  16.791  < 2e-16 ***
kappa.4       6.88917    0.37427  18.407  < 2e-16 ***
kappa.5       8.25320    0.42212  19.552  < 2e-16 ***
constant      7.28392    0.44864  16.235  < 2e-16 ***
mean.align1  -1.40745    0.24894  -5.654 1.57e-08 ***
mean.align2  -1.29975    0.22973  -5.658 1.53e-08 ***
mean.pcrs1   -0.83980    0.26990  -3.112  0.00186 **
mean.pcrs2   -1.59432    0.30632  -5.205 1.94e-07 ***
mean.vru_num -0.13055    0.01566  -8.336  < 2e-16 ***
sd.align1     0.79157    0.29234   2.708  0.00678 **
sd.align2     0.64708    0.27779   2.329  0.01984 *
sd.pcrs1      1.23104    0.23646   5.206 1.93e-07 ***
sd.pcrs2      1.54296    0.24846   6.210 5.29e-10 ***
sd.vru_num    0.08056    0.01095   7.357 1.88e-13 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Optimization of log-likelihood by BFGS maximization
Log Likelihood: -907.2
Number of observations: 576
Number of iterations: 79
Exit of MLE: successful convergence
Simulation based on 2000 Halton draws
```

Figure C.9: Output from the computation of model106_psafe

C.4. Driving stress model

The arrival delay and the load of standing passengers are additional parameters that are connected with driving stress. Perceived safety is another one factor that is expected to be related with driving stress. There are many different ways to introduce perceived safety in the model function of driving stress.

The first way is to import all the parameters of perceived safety model in the function of driving stress in order to see which of them are statically significant and which are not. In the beginning, none of these factors was selected to be random. The dataset (stress_data) that was imported for the estimation of driving stress model contained 576 observations. The individuals are distinguished according to their id (panel data). The output extracted from the computation of model200_stress is given in figure C.10. The parameter of arrival delay is the only statically significant factor for a 99% confidence interval. Align2 parameter that is connected with the existence of mixed traffic operations sections is statistically significant for a 95% confidence interval. The maximum value of the loglikelihood was calculated to be equal to -1075.

Another option was to introduce the predictions of perceived safety model in the second model about driving stress. In model201_stress that is presented in figure C.11, perceived safety is statistically insignificant for a 90% confidence interval. The betas related with the load of standing passengers and arrival delay are statistically significant for a 95% and 99% confidence interval, respectively. The maximum value of the loglikelihood was reduced by 4. Therefore, the previous model (model200_stress) represents better the population for a small confidence interval (i.e. 75%).

The last option is to add the perceived safety ratings, as they were given by each individual in each scenario, in the model function. According to the model202_stress, the psafe2 beta parameter is statistically significant for a 99% confidence interval (see figure C.12). Therefore, the feeling of safety of each tram driver impacts on driving stress. In fact, driving stress and perceived safety are both subjective notions; thus, it was expected that clear differences among the individuals will exist. The maximum value of the loglikelihood is equal to -1073. By performing a X^2, for a 99% confidence interval, it can be concluded that model202_stress represents better the population than model201_stress.

The previously presented factors were selected to be random in the estimation of model203_stress. It was assumed that random parameters follow a normal distribution. This first simulation was based on 100 Halton draws. As it can be seen in figure C.13, the mean.psafe2 is not significant for a 95% confidence interval. All the standard deviations were significant for the same confidence interval. This means that there is high heterogeneity in ”tastes” among the individuals. The maximum estimation of the loglikelihood was increased by 168. Surely (i.e. 99% confidence interval), the model203_stress represents better the population than all the previously estimated models.

Afterwards, it was decided to import familiarity in the model function instead of perceived safety. It has been mentioned that in Piraeus, the tram infrastructure is shared either with pedestrians or with the motorized traffic. According to the computed perceived safety models, non-exclusive alignments are (subjectively) unsafer than semi-exclusive alignments. For a 95% confidence interval, familiarity is a statically significant parameter, as it can be seen in figure C.14. Yet, its standard deviation is not significant; it means that familiarity is definitely not a random variable. The value of the loglikelihood was estimated to be equal to -929.

For the estimation of the final model of driving stress, only the parameters related with arrival delay and load of standing passengers were selected to be random. The simulation was based on 1000 Halton draws. As it can be seen in figure C.15, all the factors are statistically significant for a 95% confidence interval. The maximum value of the loglikelihood was estimated to be equal to -922.4. For a 99% confidence interval, the model203_stress represents better the population compared to the model205_stress (final model). Yet, the first model function contains one insignificant parameter (i.e. psafe2). Model205_stress fits better on the observations (95% confidence interval) in comparison with all the other estimated models excluding model203_stress. That is why the model205_stress was selected to be the final one.

```
Frequencies of categories:
y
      1       2       3       4       5       6       7
0.13194 0.12847 0.13889 0.21701 0.18924 0.08507 0.10938
The estimation took: 0h:0m:0s

Coefficients:
          Estimate Std. Error z-value Pr(>|z|)
kappa.1   0.864373   0.096169   8.988  < 2e-16 ***
kappa.2   1.520303   0.114050  13.330  < 2e-16 ***
kappa.3   2.449805   0.131009  18.699  < 2e-16 ***
kappa.4   3.465367   0.153033  22.645  < 2e-16 ***
kappa.5   4.169260   0.176410  23.634  < 2e-16 ***
constant  0.914662   0.301315   3.036   0.0024 **
align1    0.145497   0.240209   0.606   0.5447
align2    0.435472   0.219598   1.983   0.0474 *
align3    0.267344   0.237443   1.126   0.2602
sts       0.234189   0.167353   1.399   0.1617
pcrs1     0.065866   0.189074   0.348   0.7276
pcrs2    -0.066881   0.198737  -0.337   0.7365
time1     0.049916   0.011185   4.463 8.09e-06 ***
load      0.285848   0.209760   1.363   0.1730
vru_num  -0.012181   0.007647  -1.593   0.1112
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Optimization of log-likelihood by BFGS maximization
Log Likelihood: -1075
Number of observations: 576
Number of iterations: 76
Exit of MLE: successful convergence
```

Figure C.10: Output from the computation of model200_stress

```
Frequencies of categories:
y
      1       2       3       4       5       6       7
0.13194 0.12847 0.13889 0.21701 0.18924 0.08507 0.10938
The estimation took: 0h:0m:0s

Coefficients:
         Estimate Std. Error z-value  Pr(>|z|)
kappa.1  0.860848   0.095810   8.985  < 2e-16 ***
kappa.2  1.513271   0.113563  13.325  < 2e-16 ***
kappa.3  2.435138   0.130263  18.694  < 2e-16 ***
kappa.4  3.437575   0.151757  22.652  < 2e-16 ***
kappa.5  4.134922   0.174979  23.631  < 2e-16 ***
constant 0.751353   0.314888   2.386   0.0170 *
psafe    0.073897   0.071114   1.039   0.2987
time1    0.049007   0.009178   5.339 9.32e-08 ***
load     0.389359   0.180430   2.158   0.0309 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Optimization of log-likelihood by BFGS maximization
Log Likelihood: -1079
Number of observations: 576
Number of iterations: 65
Exit of MLE: successful convergence
```

Figure C.11: Output from the computation of model201_stress

```
Frequencies of categories:
y
      1       2       3       4       5       6       7
0.13194 0.12847 0.13889 0.21701 0.18924 0.08507 0.10938
The estimation took: 0h:0m:0s

Coefficients:
          Estimate Std. Error z-value Pr(>|z|)
kappa.1   0.870298   0.096741   8.996 < 2e-16 ***
kappa.2   1.537580   0.115135  13.355 < 2e-16 ***
kappa.3   2.476810   0.132437  18.702 < 2e-16 ***
kappa.4   3.492431   0.154395  22.620 < 2e-16 ***
kappa.5   4.197153   0.177707  23.618 < 2e-16 ***
constant  1.669681   0.268186   6.226 4.79e-10 ***
psafe2   -0.168696   0.046155  -3.655 0.000257 ***
time1     0.048052   0.009186   5.231 1.68e-07 ***
load      0.468252   0.180063   2.600 0.009309 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Optimization of log-likelihood by BFGS maximization
Log Likelihood: -1073
Number of observations: 576
Number of iterations: 54
Exit of MLE: successful convergence
```

Figure C.12: Output from the computation of model202_stress

```
Frequencies of categories:
y
      1       2       3       4       5       6       7
0.13194 0.12847 0.13889 0.21701 0.18924 0.08507 0.10938
The estimation took: 0h:0m:18s

Coefficients:
            Estimate Std. Error z-value Pr(>|z|)
kappa.1      1.62056    0.18217   8.896  < 2e-16 ***
kappa.2      2.79005    0.21612  12.910  < 2e-16 ***
kappa.3      4.37835    0.25691  17.043  < 2e-16 ***
kappa.4      6.05535    0.30818  19.649  < 2e-16 ***
kappa.5      7.18342    0.34988  20.531  < 2e-16 ***
constant     2.20719    0.34003   6.491 8.52e-11 ***
mean.psafe2 -0.05363    0.10466  -0.512 0.608401
mean.time1   0.07384    0.01439   5.131 2.88e-07 ***
mean.load    0.82818    0.22760   3.639 0.000274 ***
sd.psafe2    0.64259    0.12552   5.119 3.06e-07 ***
sd.time1     0.08276    0.01565   5.289 1.23e-07 ***
sd.load      0.65396    0.31314   2.088 0.036760 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Optimization of log-likelihood by BFGS maximization
Log Likelihood: -905.1
Number of observations: 576
Number of iterations: 129
Exit of MLE: successful convergence
Simulation based on 100 Halton draws
```

Figure C.13: Output from the computation of model203_stress

```
Frequencies of categories:
y
      1       2       3       4       5       6       7
0.13194 0.12847 0.13889 0.21701 0.18924 0.08507 0.10938
The estimation took: 0h:0m:12s

Coefficients:
           Estimate Std. Error z-value Pr(>|z|)
kappa.1     1.38106    0.15476   8.924  < 2e-16 ***
kappa.2     2.43100    0.18566  13.094  < 2e-16 ***
kappa.3     3.93926    0.22299  17.666  < 2e-16 ***
kappa.4     5.63493    0.27583  20.429  < 2e-16 ***
kappa.5     6.80388    0.32376  21.015  < 2e-16 ***
constant    1.77152    0.24399   7.261 3.85e-13 ***
mean.time1  0.08475    0.02538   3.340 0.000839 ***
mean.load   0.85171    0.30098   2.830 0.004658 **
mean.fam   -0.37919    0.16904  -2.243 0.024889 *
sd.time1    0.15363    0.02521   6.095 1.10e-09 ***
sd.load     1.46295    0.29127   5.023 5.10e-07 ***
sd.fam      0.14380    0.44462   0.323 0.746369
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Optimization of log-likelihood by BFGS maximization
Log Likelihood: -929
Number of observations: 576
Number of iterations: 71
Exit of MLE: successful convergence
Simulation based on 100 Halton draws
```

Figure C.14: Output from the computation of model204_stress

```
Frequencies of categories:
y
      1       2       3       4       5       6       7
0.13194 0.12847 0.13889 0.21701 0.18924 0.08507 0.10938
The estimation took: 0h:1m:8s

Coefficients:
           Estimate Std. Error z-value Pr(>|z|)
kappa.1     1.38962    0.15458   8.989  < 2e-16 ***
kappa.2     2.44097    0.18441  13.237  < 2e-16 ***
kappa.3     3.96246    0.22118  17.915  < 2e-16 ***
kappa.4     5.70091    0.27579  20.671  < 2e-16 ***
kappa.5     6.92761    0.32459  21.343  < 2e-16 ***
constant    1.74800    0.24215   7.219 5.25e-13 ***
fam        -0.39766    0.16732  -2.377  0.01747 *
mean.time1  0.08043    0.02051   3.922 8.78e-05 ***
mean.load   0.84309    0.31511   2.676  0.00746 **
sd.time1    0.12250    0.01615   7.587 3.29e-14 ***
sd.load     1.68996    0.32869   5.142 2.72e-07 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Optimization of log-likelihood by BFGS maximization
Log Likelihood: -922.4
Number of observations: 576
Number of iterations: 59
Exit of MLE: successful convergence
Simulation based on 1000 Halton draws
```

Figure C.15: Output from the computation of model205_stress

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