Degree Project in Computer Science and Engineering

First cycle, 15 credits

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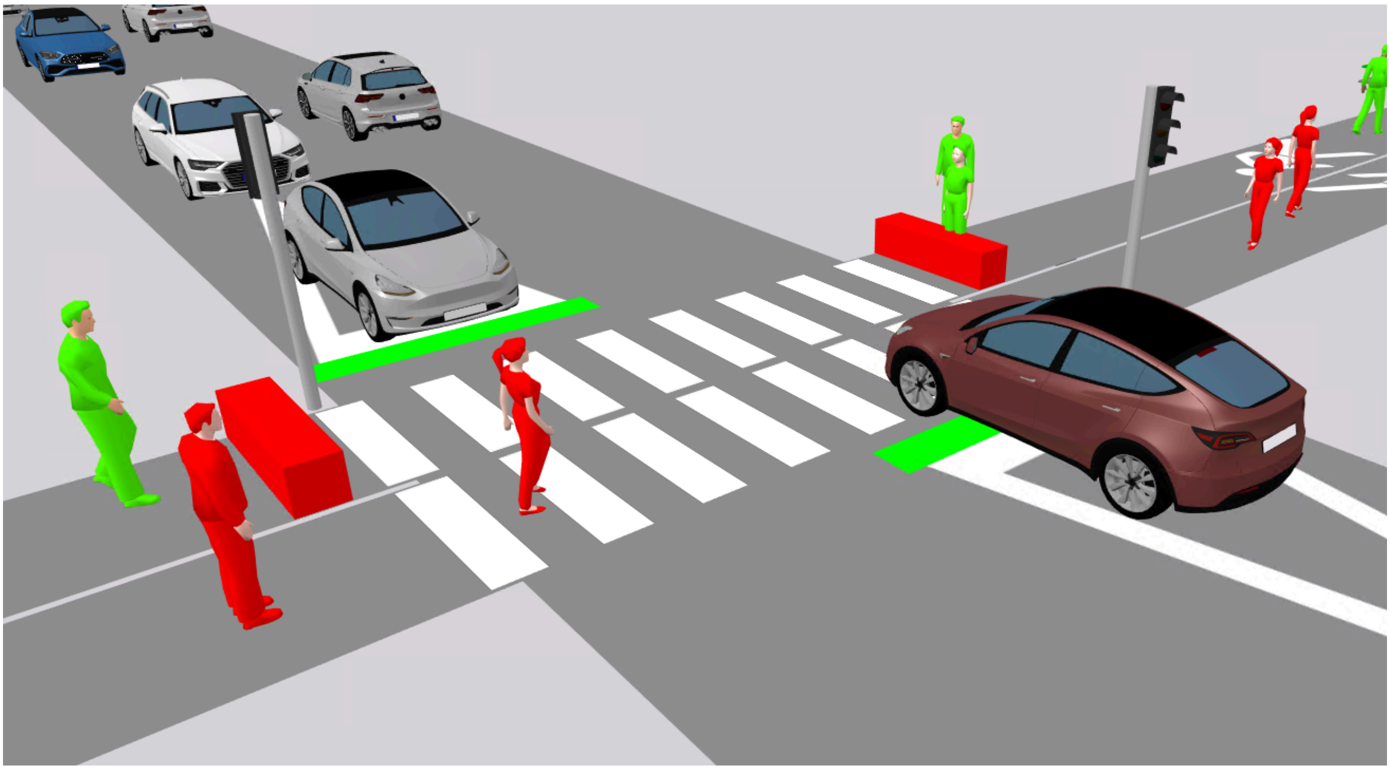

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Degree Project in Computer Science and Engineering, First Cycle 15 credits
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Abstract

Conflicts between pedestrians and vehicles are inherent in traffic systems where each participant aims to reach their destination efficiently, despite stringent traffic laws. A frequent issue arises when pedestrians cross streets without considering oncoming vehicular traffic. Such actions compel drivers to adjust their speed and direction, which can not only increase the risk of accidents but also disrupt overall traffic flow. These adjustments diminish the efficiency of the traffic system.

This study investigates the impact of jaywalking on traffic flow compared to legal crossing. Using the traffic simulation software PTV Vissim, we constructed a straight 1 km road segment with a speed limit of 70km/hour, featuring a signalized crosswalk at its midpoint. Three scenarios were devised, each varying in pedestrian crossing behaviour and quantity, simulated alongside increasing vehicle volumes. Each scenario was simulated for one hour with a 10-minute warm-up period, during which vehicle travel times were recorded. The default PTV Vissim implementations of vehicle- and pedestrian behaviour models were used for the simulation. Subsequently, a multivariate analysis was employed to examine the correlation between pedestrian behaviour and vehicle travel time.

Our findings indicate that vehicle density significantly impacts vehicle flow and travel time more than jaywalking ratio. In scenarios without pedestrians, vehicle volume increased overall travel time linearly. In scenarios with pedestrians, vehicle volume had a seemingly exponential impact on vehicle travel times. Additionally, our study revealed that in scenarios with a 100% jaywalking ratio, where every pedestrian jaywalked, overall vehicle travel time decreased by up to 50% and vehicle standstill time up to 80% compared to other ratios. This occurred because vehicles continuously had a green light, reducing the frequency of full stops. These findings suggest that signalised crosswalks might not always be the optimal solution for traffic flow. Alternatives where vehicles yield, such as unsignalised crosswalks with pedestrian precedence, could improve traffic flow in certain environments.

These discoveries contribute to a further understanding of pedestrian and vehicle interactions, highlighting the need to balance efficiency with safety. While reduced travel times may decrease urban congestion, emissions and enhance efficiency, promoting or tolerating jaywalking could undermine safety and increase accident risks. This scenario prompts a critical evaluation of whether to prioritize efficiency or uphold strict legal standards to ensure public safety. Notably, for most vehicle densities (≤ 700), jaywalking had minimal impact on travel times, suggesting that the potential efficiency gains might not justify compromising pedestrian safety.

Keywords

Traffic Flow, Jaywalking, Pedestrian-Vehicle Interaction, Traffic Simulation, Urban Traffic Management, PTV Vissim, Signalised Crosswalks, Traffic Congestion, Vehicle Travel Time, Pedestrian Safety, Traffic Density, Traffic Efficiency, Traffic System Efficiency, Unsignalised Crosswalks, Urban Planning, Traffic Regulation.

Sammanfattning

Konflikter mellan fotgängare och fordon är vanligt förekommande i trafiksystem där varje deltagare strävar efter att nå sin destination, trots stränga trafiklagar. Ett vanligt problem uppstår när fotgängare korsar gator utan att ta hänsyn till inkommande trafik. Förare tvingas att justera sin hastighet och riktning, vilket kan öka risken för olyckor och störa trafikflödet. Dessa justeringar minskar trafiksystemets effektivitet.

Denna studie undersöker effekten av otillåten korsning (s.k. jaywalking) på trafikflödet jämfört med laglig korsning. Med hjälp av trafiksimuleringsprogramvaran PTV Vissim konstruerades ett 1 km långt vägsegment med en hastighetsbegränsning på 70 km/h, innehållande ett signalreglerat övergångsställe vid mitten. Tre scenarier utformades, var och en med varierande fotgängarbeteende och mängd, simulerade tillsammans med ökande fordonsflöde. Varje scenario simulerades under en timme, efter en 10-minuters uppvärmningsperiod, under vilken fordonens restider registrerades. De förinställda PTV Vissim-modellerna för fordon- och fotgängarbeteenden användes för simuleringen. Därefter gjordes en flervariabelsanalys för att undersöka korrelationen mellan fotgängarbeteende och fordonens restid.

Våra resultat visar att fordonsdensiteten har en betydande effekt på fordonsflödet och restiden mer än förhållandet av otillåten korsning. I scenarier utan fotgängare ökade fordonens flöde den totala restiden linjärt. I scenarier med fotgängare hade fordonsflödet en till synes exponentiell påverkan på fordonens restider. Dessutom visade vår studie att i scenarier med 100% otillåten korsning, minskades den totala fordonens restid med upp till 50% och stillastående tid upp till 80% jämfört med andra fotgängarbeteenden. Detta berodde på att fordonen kontinuerligt hade grönt ljus, vilket minskade frekvensen av fullständiga stopp. Dessa resultat tyder på att signalreglerade övergångsställen kanske inte alltid är den optimala lösningen för trafikflöde. Alternativ där fordon väjer, såsom osignaliserade övergångsställen med företräde för fotgängare, kan förbättra trafikflödet i vissa miljöer.

Dessa upptäckter bidrar till en ökad förståelse för interaktioner mellan fotgängare och fordon, och betonar behovet av att balansera effektivitet med säkerhet. Även om minskade restider kan minska köer och utsläpp samt förbättra transporteffektiviteten, kan främjande eller tolerans av otillåten korsning minska säkerheten och öka olycksrisken. Detta scenario kräver en kritisk utvärdering av om man ska prioritera effektivitet eller upprätthålla strikta lagar för att skydda allmän säkerhet. Noterbart är att för de flesta fordonsdensiteter (≤ 700) hade otillåten korsning minimal inverkan på restiderna, vilket tyder på att de potentiella effektivitetsvinsterna kanske inte rättfärdigar att kompromissa med fotgängarsäkerheten.

Nyckelord

Trafikflöde, Otillåten Korsning, Gångtrafik, Trafiksimulering, Trafikhantering, PTV Vissim, Övergångsställen, Trafikljus, Trafikstockning, Fordonsrestid, Fotgängarsäkerhet, Trafikdensitet, Trafikeffektivitet, Trafiksystemeffektivitet, Oreglerade Övergångsställen, Stadsplanering, Trafikreglering

Acknowledgements

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Contents

1 Introduction

Figure 1.1: People jaywalking amid heavy traffic in Midtown.

In urban traffic environments, a fundamental goal for all participants, including pedestrians, bicyclists, and vehicle drivers, is to minimize travel time to their destinations. This leads to inevitable conflicts among different agents due to competing interests and priorities. Automated traffic management systems and regulations are designed to mitigate these conflicts, promoting a harmonious flow of traffic. However, the effectiveness of these systems is often challenged by rule-breakers and opportunists who seek to bend the rules to their advantage. Among such behaviours, jaywalking stands out as a significant factor influencing traffic congestion [1] and safety [2]. Previous research has documented the effects of jaywalking on traffic flow, suggesting that while it generally exacerbates congestion, its negative impact may diminish in conditions of high vehicular density [3][4].

1.1 Problem and Significance

Jaywalking, or the act of pedestrians crossing roads outside of designated crosswalks, presents a significant challenge to urban traffic management, leading to increased congestion, disruptions in traffic flow, and elevated risks of accidents. This study focuses on the problematic interactions between jaywalkers and vehicular traffic across different levels of traffic density and the ratio of jaywalking to legally crossing pedestrians. The unpredictable nature of jaywalking behaviour complicates the efforts of traffic engineers to design efficient and safe urban traffic systems. Understanding the specific impact of jaywalking on traffic dynamics is essential for developing effective interventions and improving overall traffic safety and efficiency in urban environments.

Measuring the impact and effects of jaywalking on traffic is highly relevant, as research in the traffic control field has the potential to impact multiple sectors positively. The reduced pollution emission following a reduction in traffic congestion impacts the environment and global development goals to mention one example [5]. Other than increased emissions of pollution, congestion also increases fuel consumption, the cost of road maintenance, and the potential for crashes [6].

To investigate these impacts and effects, a common and important tool is traffic simulations. It helps traffic planners and researchers understand relations between different agents in traffic scenarios to more effectively use available resources to solve problems. Simulation models also help users understand the effects different parameters have on traffic flow and congestion, making it a reliable and cost-effective tool.

1.2 Purpose

The objective of this study is to understand the nuanced effects of jaywalking on traffic congestion and to quantify these impacts across different traffic densities and pedestrian behaviours. By simulating these scenarios, the research aims to offer insights into how urban traffic systems can be optimized to accommodate the diverse behaviours of traffic participants, thus improving overall traffic efficiency and safety. It is important to define the scenario and context beforehand exactly, and therefore the scenario definition described in section 1.3 has been made.

1.3 Research Questions

How does pedestrian jaywalking behaviour impact vehicle flow and traffic congestion, measured in the average vehicle waiting time and overall throughput when simulated on a straight, flat, 1 kilometre long, 70km/h road with signalised crosswalks and no intersections? More specifically:

RQ1: How does the percentage p of pedestrians participating in jaywalking, in the range $0\% \leq p \leq 100\%$, with increments of 10%, impact vehicle and pedestrian travel times? See 5.1 for discussion and results.

RQ2: How does the impact of jaywalking change depending on vehicle flow, defined as the number of vehicles per hour n, within the range $100 \leq n \leq 1000$, with increments of 100, in the simulation? See 5.1 for discussion and results.

To answer these research questions, three different scenarios were defined, each with varying pedestrian behaviours and quantity, alongside increasing vehicle volumes (see 3.3).

Hypotheses

Previous observational studies on the effects of jaywalking show that jaywalking negatively affects traffic flow, and that it has a much greater impact on traffic flow compared to legal crossing sections [3][4]. Another article found that pedestrian crossing has less of an impact when the density of vehicles is high [7]. As jaywalking creates similar responses from vehicles with regards to slowing down and yielding, though possibly at varying rates for jaywalking and legal crossing, as modeled by observational studies [8][9], we expect jaywalking to show a similar pattern. Another study on jaywalking influence on traffic flow specifically found that jaywalkers choosing to cross at a higher speed increased the maximum vehicle flow [4]. The expected outcome for each research question is described below.

- RQ1: Based on the results of previous observational studies we hypothesize that the number of pedestrians participating in jaywalking behaviour will have a greater negative impact on traffic flow compared to legal crossing behaviour.
- RQ2: Prior research has found that pedestrian crossing has less of an impact on higher traffic density. We therefore expect a high jaywalking ratio to not impact the flow of traffic as much, as vehicle flows increase. We expect jaywalking to have a bigger effect on congestion when vehicle flow is lower, as there will be less congestion caused by the vehicles themselves.

1.4 Goal and Stakeholders

By exploring the nuanced effects of jaywalking on traffic congestion, the goal of this study is to contribute to the broader understanding of traffic dynamics and offer evidence-based recommendations for urban traffic management and pedestrian safety strategies. By providing insights into how pedestrian behaviours influence traffic flow, this research has the potential to inform policy, urban design, and traffic management practices. It seeks to find a balance between different agents in a traffic environment, supporting broader goals of sustainability and public health.

Stakeholders

The main stakeholders for this project are urban planners and companies responsible for traffic control. By examining the results of simulations such as this one they can identify the most effective measures for improving traffic flow and reducing the overall congestion. As these insights and actions also reduce the pollution caused by traffic congestion it is also beneficial for stakeholders interested in furthering the work towards the Sustainable development goals [5].

Other stakeholders are pedestrians and drivers who commute by car. The goal of this project is to gain insight into traffic scenarios these stakeholders participate in, and offer recommendations for improvements in traffic scenarios and urban planning. As such, improvements made because of those insights and recommendations will directly affect how these stakeholders traverse traffic on a day-to-day basis.

1.5 Scope and Delimitations

Simulating traffic environments is complex, with many parameters that affect the outcomes. To keep the simulation simple whilst retaining realism, several limitations were placed on the implementation and scenarios.

Firstly, a limit was placed on the vehicles measured by the simulation, as different traffic scenarios can include a variety of different vehicles such as cars, trucks, bikes, wheelchairs, etc. For this study, the simulation was limited to only include cars and pedestrians. As such, any reference to *vehicles* in the simulation throughout this thesis will refer to *cars*.

Secondly, for simplicity and various technological limitations, *pedestrians* throughout this thesis will only refer to fully able-bodied adult humans walking on foot.

The traffic simulation was limited to a straight, 1 kilometer long, single-lane vehicle road in each direction with no intersections apart from pedestrian crosswalks.

More specific details about the delimitations on the implementation to achieve the scope can be found in section 3.5. More advanced simulations, encompassing broader scenarios are out of the scope for this thesis and will be left as future work.

1.6 Outline

The upcoming background chapter (2) gives an overview of traffic and pedestrian models that are used in the simulation, along with previous research in this field, the choice of simulation tool and the ethical implications of the research.

The method chapter (3) describes the precise implementation details of the simulation, simulation parameters and measurements used, and how they help answer the research questions presented in the introduction.

The simulation results are presented in the results chapter (4). Results are followed by their analyses in the discussion chapter (5), ending with suggestions for improvements and future work. These discussions will be concluded and summarised in the conclusion chapter (6).

2 Background

In the evolution of urban traffic dynamics, the transition of streets from shared public spaces to vehicular domains has introduced the practice of jaywalking. Historically, as cities began to accommodate the increasing presence of automobiles, the term "jaywalking" was coined and utilized by automotive interest groups to often stigmatize pedestrian use of streets [10]. This societal shift reflects the broader contest between pedestrian rights and vehicular flow, a core focus of this study.

Previous research, including Roy J. Wang's 2009 thesis on the effects of jaywalking [3] and subsequent studies by Zheng and Huang, underscores the significant impact of pedestrian behaviours on traffic dynamics [3] [8]. These studies, through simulations and real-life data modelling, illustrate varying degrees of jaywalking's influence on traffic congestion and safety. This thesis builds upon these findings, delving deeper into the relationship between jaywalking, traffic density, and pedestrian behaviour.

As urban areas increase in density, the interaction between pedestrians and vehicles becomes increasingly complex. The need for efficient and safe traffic systems is paramount in promoting sustainable urban mobility. Understanding jaywalking within this context is crucial for developing traffic management strategies that accommodate the natural pedestrian flows while minimizing disruptions to vehicular traffic.

2.1 Modelling Traffic Scenarios with PTV Vissim

Simulations will always be an approximation of reality. For any given simulation scenario attempting to model the real world, it is important to choose an accurate tool. Among several different traffic simulation tools available on the market, in this thesis, PTV Vissim will be used.

Motivation for Choosing PTV Vissim

PTV Vissim is a flexible software for traffic simulation, widely recognised for its detailed modelling capabilities of traffic patterns and behaviours in urban and suburban environments. It supports a multidimensional approach to traffic analysis, including vehicles, pedestrians, and cyclists, making it an ideal tool for simulating complex, multi-modal interactions in traffic systems. Especially relevant to this thesis, PTV Vissim's strength lies in its microscopic modelling approach, where individual entities in the traffic system are simulated with unique characteristics and behaviours.

This level of granularity allows for a nuanced analysis of traffic phenomena, such as jaywalking, and its impact on traffic flow.

The use of PTV Vissim in this study is motivated by its proven track record in academic and professional studies focusing on traffic management, road safety, and urban planning. Its dynamic simulation environment and robust data analysis tools enable us to accurately model the behaviour of jaywalkers and assess their influence on vehicle flow and congestion. Furthermore, the flexibility available when creating scenarios makes it possible to explore various traffic densities and pedestrian behaviours, which directly aligns with our research objectives.

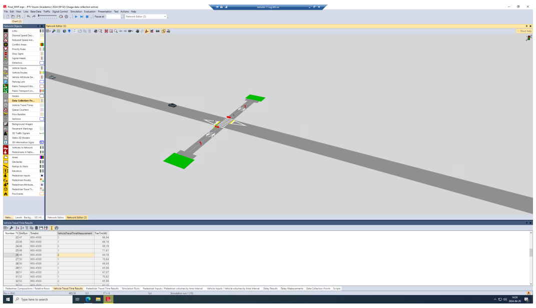

Figure 2.1: Screenshot of the main user view in PTV Vissim, showing the layout of the software. The viewport is set to 3D mode and a basic network setup can be seen.

By leveraging PTV Vissim, we aim to provide an empirical basis for understanding the implications of jaywalking in urban traffic systems. The software's comprehensive simulation capabilities will allow us to examine the interactions between pedestrians and vehicles under different conditions, offering insights into effective traffic management strategies that can mitigate the negative impacts of jaywalking.

2.2 Previous Studies and Investigations

There have been several different papers investigating jaywalking similarly. One of the most relevant to our thesis is Roy J. Wang's 2009 Master thesis *Simulation Based Evaluation on the Effects of Jaywalking* [3], where he collected data on jaywalking behaviour and how it affected traffic flow in Newark, DE along East Main Street and then used the software PTV Vissim[1] to simulate a recreation of this environment based on data gathered. This was done to evaluate how different behaviours of jaywalking affected traffic flow. Roy J. Wang found that legally crossing pedestrians at signalized locations doesn't significantly impact traffic. However, the inclusion of pedestrians at midblock crossings and jaywalkers significantly increased travel time and delay for vehicles. The presence of jaywalkers, who cross at various points outside of midblock crossings, notably raised travel time and delay, highlighting the

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[1] PTV Vissim's official website: https://www.ptvgroup.com/en/products/ptv-vissim (accessed 16-2-2024)

substantial impact of jaywalking on traffic flow.

Several papers have, based on real-life data reported by study participants, attempted to model jaywalking behaviour and how vehicular traffic interacts with it. Two papers stood out as the most relevant to our analysis, and these are *Modeling vehicle-pedestrian interactions outside of crosswalks* by Yinan Zheng et al. from 2015 and *Research for Urban Traffic Simulation Model of Cross-street Pedestrian Influence* by Ruijin Huang from 2018.

There have also been research papers implementing a cellular automaton simulating jaywalking [11][4], using "a microscopic simulation model for pedestrians and vehicles" [12], amongst others, which seem to, for the most part, agree in terms of how much jaywalking affects traffic flow.

2.3 Ethics and Sustainability

One of the primary advantages of this project is its reliance on simulation to study traffic behaviours and pedestrian interactions. This approach eliminates the risks associated with real-world experiments in urban environments, ensuring that no pedestrians nor drivers are put in unsafe situations. No harm will come to any participants, which is a foundation for ethical research. Additionally, simulations avoid concerns about privacy related to data collection from real individuals.

The sustainability implications of this research include environmental, social and economic benefits.

The simulations aim to identify strategies for improving traffic flow, which can have various environmental benefits; reduced vehicle emissions, cleaner air quality and overall smaller carbon footprints [13].

Socially, this research project aims to highlight the importance of improving pedestrian safety, convenience and health, with potential to encourage more active lifestyles and access to urban spaces on foot. As mentioned previously, this study aims to contribute to reducing vehicular congestion. This reduction is pivotal, as demonstrated by studies on traffic-related air pollution, which have linked increased polluting air particle concentrations from congested to significant negative impacts on public health, including excess morbidity and mortality among drivers, commuters and residents near major roadways [14].

Economically, optimizing traffic systems through simulation can reduce costs associated with congestion, such as fuel consumption, road maintenance, and healthcare costs from traffic-related injuries. This research aligns with the broader goals of sustainable urban development, aiming to create livable cities that cater to the needs of all inhabitants while minimizing environmental impact.

By aiming to aid in the research towards mitigating congestion and, consequently, lowering pollutant emissions, this research indirectly addresses public health concerns, showcasing the broader societal benefits of improved traffic systems beyond simple efficiency and safety.

3 Method

This section of the thesis will describe the implementation performed for the experiment. First, a description of the traffic simulation and how it was constructed is explained in sections 3.1 and 3.2, followed by an explanation of the data collection from the simulation runs in section 3.4. Section 3.3 then details the three different scenarios S1, S2, S3 compared in the simulation, and how the data from each scenario was used. Lastly, section 3.5 lists the delimitations made for the traffic simulations, to preserve the scope of the project. The complete PTV Vissim file of the simulation implementation, as well as the files and data used for data visualisation, can be found in Appendix A.

3.1 Simulation Overview

To investigate the dynamics of jaywalking, a traffic simulation on a single street with one traffic light was created.

The simulation was implemented in the software PTV Vissim, a traffic simulation software capable of creating street environments with basic traffic control systems, vehicles, and pedestrians. In this implementation, the default pedestrian and vehicle parameters were used whenever possible, which are accurate when properly calibrated based on scenario [15]. The software comes with its own implementations of pedestrian- and vehicle behaviour.

Behavioural Models

PTV Vissim utilizes an implementation of the Wiedemann 74 car-following model as its default model for simulating vehicle behaviour. This model, developed by Rainer Wiedemann in 1974 at Karlsruhe University, describes how drivers react to the vehicle ahead, focusing on maintaining a safe distance based on speed and acceleration differences. It accounts for different driving states such as free driving, approaching, following and braking [16].

For pedestrian behaviour, PTV Vissim uses the Social Force Model. This model represents pedestrians as particles subjected to social forces, which include attraction to destinations, repulsion from obstacles and other pedestrians, and personal motivation to maintain a comfortable walking speed and direction [17].

3.2 Construction of Simulation Environment

Model construction began by creating the 1000 meter single-lane, bidirectional road. This was done using the *Link* item in PTV Vissim, which is the built-in road function in the software. The parameters for the road were kept as the default option whenever possible, with the speed limit assigned to 70km/hour. A *Vehicle Input* was then assigned for each direction of the road, which instantiates cars continuously based on the defined parameter of cars per hour. The cars instantiated will then follow the specified speed limit, with a default degree of random variation, and abide by all traffic rules until they reach the end of the road. Figure 3.1 shows this road, with cars instantiated in both directions.

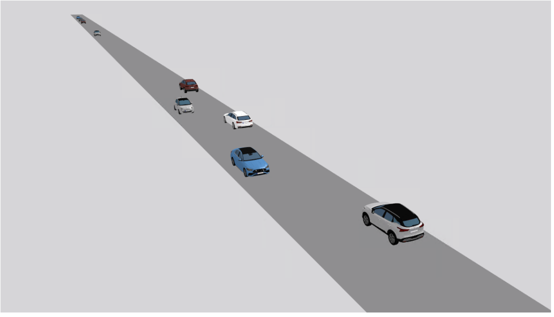

Figure 3.1: Screenshot of the 1000-meter single-lane, bidirectional road with cars instantiated from both directions. The cars freely drive on the road until they encounter an obstacle. Obstacles in this simulation include both jaywalking pedestrians and signalised crosswalks.

Figure 3.2: Screenshot of one end of the road segment, or the *link*. The thin coloured lines at the end of the *link* are the vehicle input point and the time measurement marker.

Following the road and vehicles, the crosswalk was implemented in the exact middle of the motorized road. This was done using the *Link* function similar to the road but resized and assigned as a "pedestrian walkway" in the software. This is a built-in functionality in PTV Vissim, which converts a road into a walkway for pedestrians. This walkway was divided into two halves, one for legal crossing with a red light and another for jaywalking where the pedestrians do not wait for cars to have a stop signal. The entire crosswalk was then given a traffic signal, with sensors for the cars and legally crossing pedestrians to control the lights. The traffic light uses the default algorithm in PTV Vissim to control the traffic signals through these sensors. The following traffic rules were then defined for the crosswalk:

1. Pedestrians crossing on the legal walkway always wait until they receive a

green light.

2. Pedestrians crossing on the jaywalking walkway never yield to cars, instead simply continuing to walk regardless of the traffic light signal.
3. Cars always stop for a red light and go on a green light but will yield if a jaywalker is crossing the street, even if the car has a green light, to avoid collision.

Pedestrian inputs were then created on each side of the pedestrian walkways (green areas in Figure 3.3). These work the same way as vehicle inputs, instantiating pedestrians based on a parameter for people per hour. Figure 3.3 shows this implemented crosswalk, as shown from above.

To define which pedestrians choose the legal pedestrian lane and the jaywalking pedestrian lane, a *partial routing decision* was created (red and blue dots in Figure 3.3). *Partial routing decisions* is a tool in PTV Vissim that allows certain pedestrians to be assigned to move through specific areas based on their specific attributes. For this implementation, two different types of pedestrians were created: legally crossing pedestrians and jaywalkers. The simulation instantiates these two types of pedestrians according to a *relative flow* parameter. The *relative flow* parameter asserts what ratio of the total instantiated pedestrians should be of a specific attribute. For example, if the *relative flow* parameter for the jaywalkers is set to 0.3 and for legally crossing pedestrians it is set to 0.7, then 30% of all instantiated pedestrians will be jaywalkers.

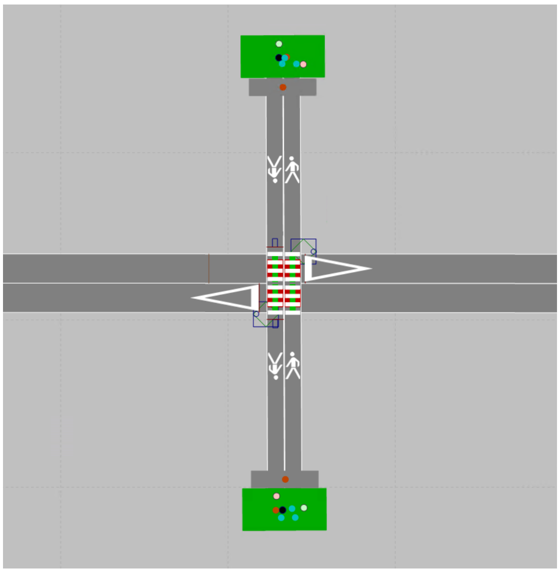

Figure 3.3: The signalised crosswalk in more detail. The green areas are instantiation points for pedestrians in the simulation. Pedestrians walk to the green area on the opposite side of the main road. Legal pedestrians wait for the traffic lights to turn green before crossing the street and jaywalking pedestrians simply cross with no regard for oncoming traffic or traffic lights.

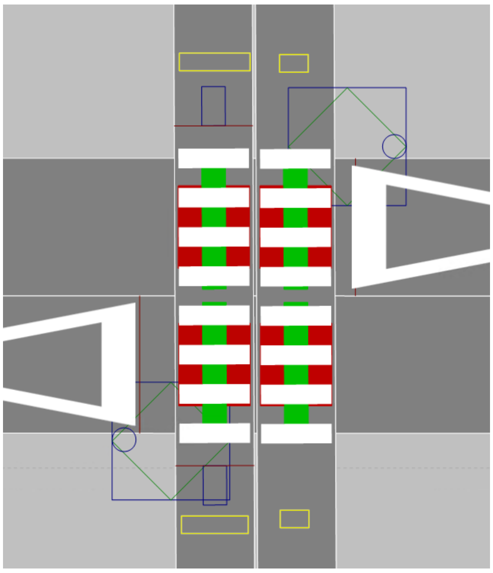

Figure 3.4: Pedestrian areas used by the pedestrian routing decision points (yellow squares). Non-jaywalking pedestrians go on the right lane, jaywalking pedestrians go on the left lane. Blue squares show markers for traffic lights.

Once these attributes were defined for jaywalkers and legally crossing pedestrians respectively, those attributes were assigned to be checked by the *partial routing decision*. This means that if a pedestrian is of the jaywalker type it will be assigned to move through the jaywalking crosswalk on the right and legally crossing pedestrians through the legal crosswalk on the left. A more detailed image of this crosswalk with these *routing decisions* implemented can be seen in Figure 3.4, where the yellow squares are the areas the pedestrians are assigned to walk through depending on their attribute to ensure that they choose the correct lane.

For a more clear view of the simulation as well as easier troubleshooting, the pedestrians were also assigned colours depending on their attributes. If the pedestrian is of the Jaywalker type they will be dressed all in red, whereas if they are of the legally crossing pedestrian type they will be dressed all in green.

The simulation has a warm-up time of 900 simulated seconds before any measurements are taken, after which it runs for 3600 simulated seconds. The simulation warm-up time allows for the system to reach a homeostatic state, resulting in more accurate data. Every simulation run is performed 10 times by the program, with a different seed each time. The beginning seed is 42 (PTV Vissim standard seed) and the seed is incremented by 1 each run. Figure 3.5 shows the simulation running with all the implemented features described above.

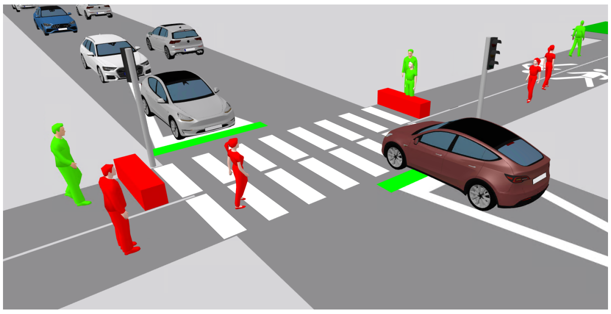

Figure 3.5: A simulation in progress in 3D-mode. Pedestrians crossing legally are completely green and jaywalking pedestrians are completely red. The red cuboids on the streets indicate that the lane is currently stopped because of the signalised crosswalk. The green cuboids indicate that the lane is open.

3.3 Scenarios

Inspired by the work of Roy J. Wang [3], this simulation explores three distinct scenarios to gauge the impact of jaywalking on vehicle traffic and collect our evaluation data.

S1: Vehicle traffic without pedestrian crossings.

S2: Vehicle traffic with pedestrian crossings, where pedestrians cross only on a green light.

S3: Vehicle traffic with pedestrian crossings, incorporating a mix of pedestrians who wait for the green light and those who jaywalk without waiting for a signal. The ratio of jaywalking to non-jaywalking pedestrians and vehicle amount will be varied to assess the impact on vehicle traffic flow, as per RQ1 and RQ2.

Data gathered from scenarios 1 and 2 were used to assess the impact of legally crossing pedestrians on traffic flow, establishing a base case. Subsequently, a similar analysis comparing scenarios 1 and 3 to evaluate the effects of illegal pedestrian crossing was done. By comparing these two sets of measurements, a statistical evaluation was done to determine the significance of jaywalking's impact compared to legally crossing pedestrians on traffic flow. This data is presented in section 4. A picture of each scenario being simulated can be found in figure 3.6.

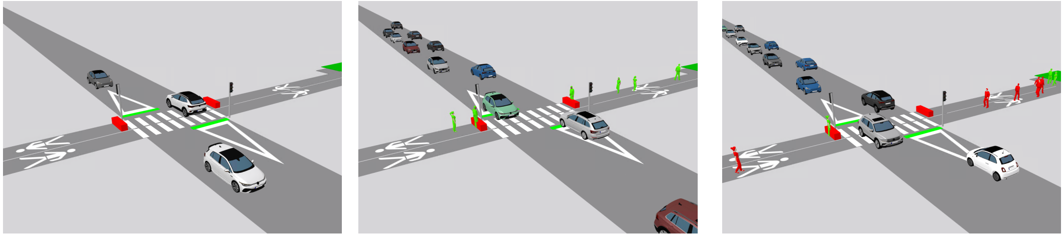

Figure 3.6: Pictures of all three scenarios being simulated. The left figure shows scenario S1, vehicles always have a green light because of no pedestrians. The middle figure shows scenario S2, with pedestrians crossing legally (in green). The right figure shows scenario S3, with a mix of legally crossing pedestrians (in green) and jaywalking pedestrians (in red) crossing the road.

3.4 Data Collection and Evaluation Measurements

To be able to answer the research questions presented we identified the following evaluation measurements to collect from the simulation.

Label	Measures/Comparisons	RQ Links (see 1.3)	Scenario (see 3.3)
E1	Vehicle travel time (s)	RQ1, RQ2	S1, S2, S3
E2	Vehicle flow (Vehicles/hour)	RQ2	S1, S2, S3
E3	Jaywalking ratio (%)	RQ1, RQ2	S2, S3
E4	Vehicle standstill time (s)	RQ1, RQ2	S1, S2, S3
E5	Pedestrian travel time (s)	RQ1, RQ2	S2, S3

Table 3.1: Evaluation Labels and Priorities

At the beginning and end of each vehicle lane, a *time measurement* object was placed to collect the vehicle travel time (E1 in Table 3.1). When a vehicle is initiated into the simulation, the time measurement will pick it up at the beginning and a timer for that vehicle will begin. Once it reaches the end of the road, the timer will stop, resulting in a total travel time from the start to the end destination for each vehicle. PTV Vissim then calculates the average travel time for all vehicles, giving us the data for that simulation run. For our implementation, where each simulation is run a total of 10 times with varying seeds for randomness, PTV Vissim also calculates the average for all of these runs which is the data we collect.

The vehicle flow value (E2 in figure 3.1) is passed as a parameter into the simulation and as such it is defined by the user before each simulation starts. The pedestrian flow value for the simulation is a static variable, set to $213, 25$ pedestrians/hour in each direction. The value was chosen based on a previous observational study in Calgary, Canada [18]. The value was measured on 3 Street /Avenue SW during the AM Peak Period (7:00-9:00) on May 2nd 2008, where the total number of pedestrians in all directions for the entire time interval was measured to 853. A value based on previous observational studies was chosen to make the simulation as realistic as possible, as opposed to choosing an arbitrary value.

Institutional Constraints and COM-Interface Access

We originally planned to use the COM-Interface within PTV Vissim for altering input values of the simulation runs. The COM-Interface allows the user to make changes to a scene programmatically, allowing automation of changes to input values and data export, between runs. This would have allowed a multi-dimensional analysis, where pedestrian flow, for example, could have been varied as well. However, due to institutional constraints and difficulties getting access to the COM-Interface due to it being locked behind admin access on available computers, all simulation runs, parameter changes and data extractions were done manually. Because of the exponential nature when introducing more varying variables, also making changes to pedestrian flow would have been unreasonable for our time plan. For future work within this field, it is advised to prioritise getting access to the COM-Interface to alleviate this limitation.

3.5 Delimitations

Several delimitations were made to keep the implementation within the scope of the thesis.

Default parameters and behavioural models for the cars and pedestrians were used throughout the project (see 3.1 for more details). This includes using default, stochastic speed parameters for all pedestrians as well as vehicles.

Furthermore, the implementation of jaywalking behaviour in the simulation is simplistic. A pedestrian in the simulation either jaywalks or doesn't, which isn't a realistic reflection of real-life behaviour where jaywalking occurs based on many parameters. These parameters include the gap to the next car, variable speed, and inclinations towards jaywalking, among others [8]. Discussions of these delimitations, among other limitations, is done in section 5.4.

4 Results

The beginning of this chapter presents a summary of results (4.1) collected from the traffic simulations, and presents main findings. The following subsections present the results for each scenario in more detail.

4.1 Summary of Results

The results of the study show that vehicle flow increases affect vehicle travel time linearly when there are no pedestrians, and appear to do so exponentially with pedestrians. At lower vehicle flows (800 and below), the jaywalking ratio had minimal impact on vehicle travel time. A jaywalking ratio of 0 (only legally crossing pedestrians) resulted in faster travel times compared to ratios of $0.1-0.5$. At higher vehicle flows, the differences in jaywalking ratios became apparent: a jaywalking ratio of 0.6 led to faster vehicle travel times compared to only legally crossing pedestrians. This improvement increased as the jaywalking ratio increased, and was optimal when the jaywalking ratio was 1. Additionally, the overall standstill time was comparatively lower than the travel time differences at high jaywalking ratios.

Pedestrian travel times were faster the more evenly split the pedestrians were between jaywalking and crossing legally. However, the difference was small. Only an increase of 8% was found when comparing the highest and lowest pedestrian travel time results.

4.2 Scenario S1: No Pedestrians

The simulation results for S1 are shown in figure 4.1. This scenario serves as the base case for all other scenarios. In this scenario, for all vehicle flows ranging from 100 to 1000 vehicles per hour, the average vehicle travel time was found to have a positive correlation with vehicle throughput. This means that as the number of vehicles per hour increases, the average travel time for each vehicle also increases. This observation is fundamental and logical, providing a clear benchmark for more complex scenarios.

4.3 Scenario S2: Green Light Crossings

The simulation results for S2 are also shown in figure 4.1. As expected, the vehicle travel time increased when pedestrians were introduced in the second scenario. For the lower values of vehicle flow ($100 \leq n \leq 500$) the increase in travel time was between 7 and 11 seconds, with steady increases as the vehicle flow amount increased.

However, vehicle travel time grew more rapidly for each increment of vehicle flow. For high amounts of vehicle flow ($n = 1000$) the increase in vehicle travel time was 150 seconds, meaning a total travel time increase of approximately 400% compared to the base case in scenario 1.

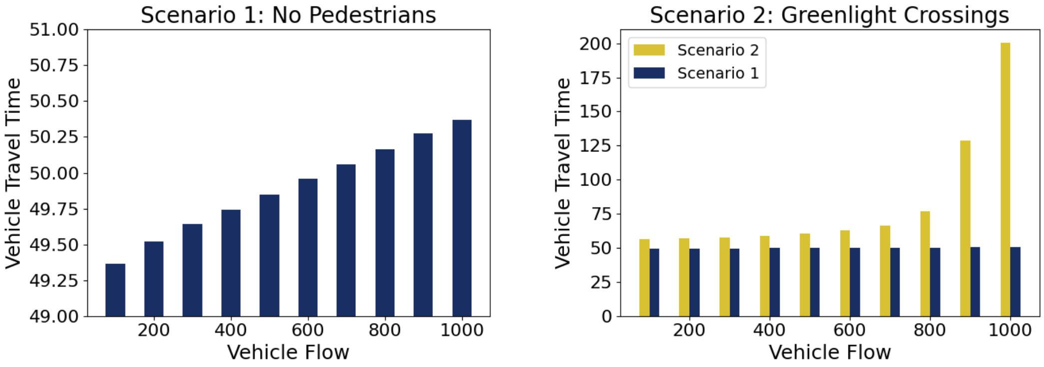

Figure 4.1: The average travel time for each vehicle in scenarios S1 (left) and S2 with S1 added for reference (right). Both graphs plot the Vehicle travel time (E1 in table 3.1) on the Y-axis and the Vehicle flow (E2 in table 3.1) on the X-axis. The travel time in S1 increases linearly, while the travel time in S2 increases more rapidly as vehicle flow increases.

4.4 Scenario S3: Mixed Behaviour Crossings

This scenario simulates a mix of jaywalking and non-jaywalking pedestrians with varying vehicle flows. For more details on how the vehicle flow and jaywalking ratio parameters are varied see section 1.3 where they are defined in our research questions.

Vehicle Travel Time Results

The average vehicle travel time depicted in figure 4.2 is defined as the average time it took for each vehicle to reach the other end of the 1 km road. The results show that vehicle flow had the greatest impact on the overall travel time, causing a seemingly exponential increase similar to the results shown in scenario 2, see figure 4.1. The result also shows that jaywalking had the highest impact on high flows of traffic and that the simulations with 100% jaywalking ratio were the most efficient for almost all vehicle flows. Especially for the highest flows of traffic ($900 \leq n \leq 1000$), where the simulations with 100% jaywalking ratio had up to a 49% decrease in vehicle travel compared to other jaywalking ratios.

A jaywalking ratio of 0 (only legally crossing pedestrians) resulted in faster travel times compared to ratios of $0.1 - 0.5$. However, when compared to ratios ≥ 0.6 the jaywalking ratio of 0 resulted in slower travel times.

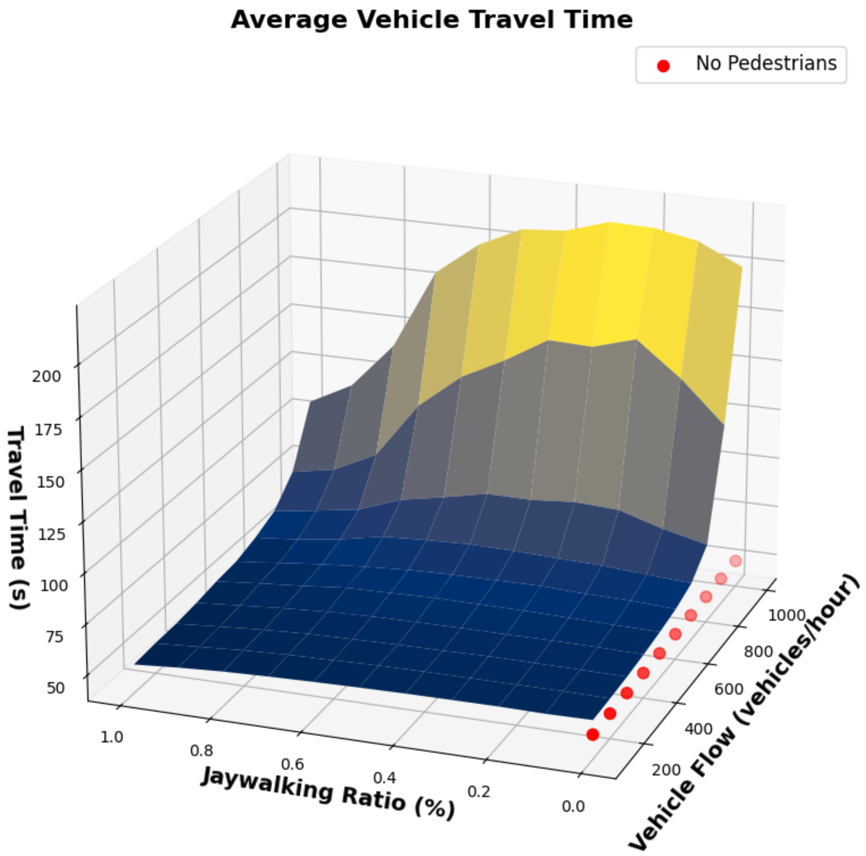

Figure 4.2: Average travel time per vehicle in scenario S3, shown in a 3D surface plot with Jaywalking Ratio and Vehicle Flow as variables. The base case S1 with no pedestrians is also included for comparison. The plot reveals that vehicle flow impacts travel time more significantly than the jaywalking ratio. It also shows that the vehicle travel time was at its lowest when the jaywalking ratio was at its highest.

Vehicle Standstill Time Results

In each simulation, data on the duration each vehicle remains completely stationary was collected. Overall the results closely resemble the one in figure 4.2, showing that the amount of standstill time increases at a similar rate as the overall travel time increases. The only noticeable difference in vehicle standstill time increase occurred when the jaywalking ratio was very high (ratio $0.9 - 1$), where the standstill time increased significantly less in comparison to its overall travel time increase.

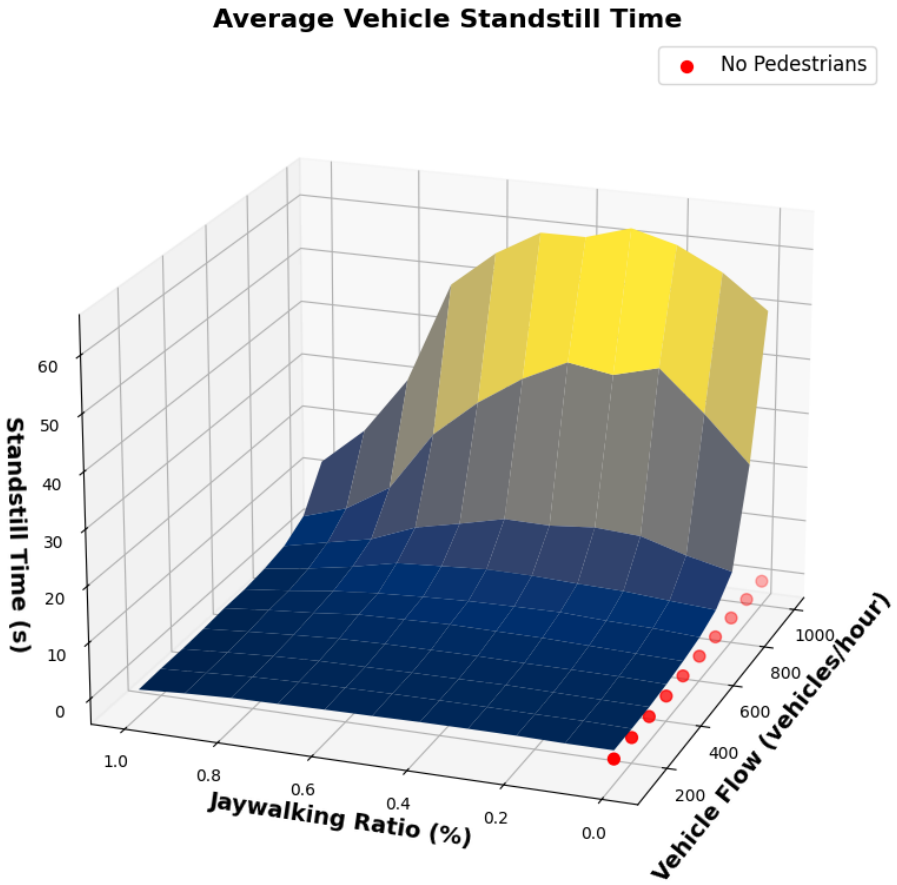

Figure 4.3: Average travel time per pedestrian in scenario S3 depicted in a 3D surface plot with Jaywalking Ratio and Vehicle Flow as variables. The plot almost perfectly mirrors figure 4.2, except that the standstill time decreases more rapidly as the jaywalking ratio approaches 1.

Pedestrian Travel Time Results

Figure 4.4 shows the measurements for pedestrian travel time in all scenarios. The results indicate that the average pedestrian travel time is lowest when the jaywalking ratio is balanced. Travel time peaks when all pedestrians are jaywalking. The differences may seem large, but the plot range is relatively small. Comparing the highest measured pedestrian travel time with the lowest measured gives an increase of about 8%.

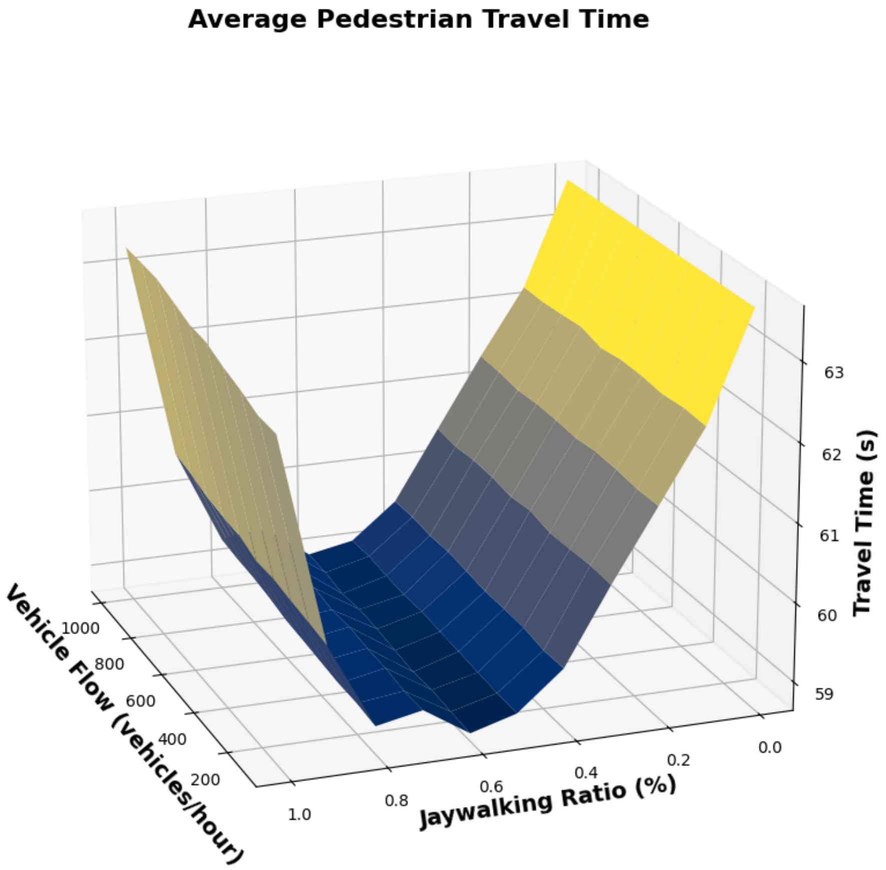

Figure 4.4: Average travel time per pedestrian in scenario S3 depicted in a 3D surface plot with Jaywalking Ratio and Vehicle Flow as variables. The results show that the more evenly the pedestrians were divided between jaywalking and crossing legally, the lower their average travel time was.

5 Discussion

This chapter begins with a summary of our key findings in section 5.1, presented by answering each research question listed in section 1.3. Subsequently, a more detailed interpretation of our findings will be described in section 5.2 and the implication of these findings will be explored in section 5.3. Lastly, a discussion regarding the limitations of our study and propositions for future research will be given in sections 5.4 and 5.5, respectively.

5.1 Summary of Key Findings

Below is a summary of the main findings of our research, listed according to our research questions from section 1.3. For a more detailed description, see section 5.2.

RQ1

How does the percentage p of pedestrians participating in jaywalking, in the range $0\% \leq p \leq 100\%$, with increments of 10%, impact vehicle and pedestrian travel times?

Our findings indicated that for most vehicle densities ($n \leq 700$), the percentage of both pedestrians jaywalking and pedestrians crossing legally had minimal impact on vehicle travel times. However, for higher density of vehicles ($n \geq 800$) the ratio of jaywalking had a significant positive impact compared to legal crossing behaviour, with very high jaywalking participation being optimal for vehicle travel times. This is a contradiction to our hypothesis based on previous studies, which found that jaywalking leads to a much greater increase in travel time for vehicles compared to legal crossing behaviour [3][4]. The increased jaywalking ratio decreased the use of the pedestrian traffic signal, increasing green light time for vehicles and thus reducing overall standstill time.

RQ2

How does the impact of jaywalking change depending on the vehicle flow, defined as the number of vehicles per hour n, within the range $100 \leq n \leq 1000$, with increments of 100, in the simulation?

Higher vehicle densities significantly amplified the impact of jaywalking and legal pedestrian crossings on traffic flow. The scenario with only vehicles indicated a linear growth in vehicle travel time as vehicle density increased. However, when pedestrians were present in the simulation, the impact on vehicle travel time seemingly grew exponentially as vehicle densities increased. This contradicts prior research in the field, claiming that pedestrian crossing has less of a negative impact on traffic flow when vehicle density is high [7]. However, for greater vehicle densities, jaywalking led to a decrease in vehicle travel time compared to legal crossings. This confirms our original hypothesis, where we expected jaywalking to have less of a negative impact on high traffic densities, compared to legal crossing behaviour.

5.2 Analysis and Correlation to Research Questions

This section contains a more detailed description of our findings, analysing each scenario and explaining how they relate to the key takeaway for our research question, as described in section 5.1.

Scenario S1: No Pedestrians

The linear increase in vehicle travel time in the absence of pedestrians (scenario S1) establishes a baseline, confirming the expected correlation between increased vehicle flow and extended travel times. This scenario highlights the inherent delays that follow from higher traffic flows, such as keeping an appropriate distance from leading vehicles. This baseline helps us analyse the impacts of jaywalking and changes in vehicle flow, which further can help us answer both RQ1 and RQ2.

Scenario S2: Green Light Crossings

The introduction of pedestrians in scenario S2 significantly alters traffic dynamics, where vehicle travel time appears to increase exponentially with vehicle flow. This growth highlights the disruptive effect of pedestrian crossings on vehicle flow, particularly at higher traffic volumes. This finding is interesting with regard to urban planning, indicating that even legal pedestrian behaviour can considerably slow traffic, especially under conditions of high vehicle density. This scenario provides essential insights for answering both RQ1 and RQ2. Understanding the delays caused by the general presence of pedestrians is crucial for analyzing the specific delays resulting from jaywalking behaviour.

As prior research has found pedestrian crossing to have less of a negative impact on vehicle travel times when vehicle density is high [7], our findings stand in direct contradiction. This further highlights the complex interplay between pedestrians and vehicles, suggesting that different traffic environments might yield different results. This could be a result of our chosen implementation, since using the signalised crosswalk which gives all vehicles a red light was the only routing option for pedestrians crossing legally. A more complex traffic environment, with multiple roads, intersections and crossways or pathways for pedestrians, giving each agent multiple options in their route, could potentially give a more realistic representation of real traffic scenarios.

RQ1 & RQ2 with Scenario S3: Mixed Behaviour Crossings

Scenario S3 presents the most complex results, showing that high jaywalking ratios paradoxically can decrease vehicle travel times, especially at high traffic densities. This counter-intuitive outcome is explained by the fact that increases in jaywalking ease traffic flow by reducing the frequency and duration of full stops at the signalised crossing, which is also shown by figure 4.3. Figures 4.4 and 4.2 both look similar, but it is clear that the average vehicle standstill time comparatively decreases more at higher jaywalking ratios than the average vehicle travel time.

As mentioned, the significant difference in stop time is a direct result of pedestrians using the traffic signals to a far lesser extent. This results in vehicles having higher up-time of green traffic signals, ensuring fewer full stops for pedestrians crossing. Instead, vehicles employ methods of yielding to pedestrians by slowing down when spotted from a distance, allowing for more dynamic interactions between pedestrians and drivers.

These results contradict previous studies, which found that jaywalking leads to a much greater increase in travel time for vehicles compared to legal crossing behaviour [3][4]. One explanation of this could be the fact that simulation environments, such as our implementation, remove aspects of human decision-making that normally take place in traffic environments. In a simulation all pedestrians walk perfectly, all vehicles drive perfectly and they can all sense each other at all times. In a real-world scenario aspects such as field of view, reaction time and awareness all impact the effectiveness and safety of unsignalised crossing.

RQ1: Pedestrian Travel Times

A surprising outcome from the simulations was that pedestrian travel times were the lowest when the jaywalking ratio was balanced (see 4.4). We hypothesised that the pedestrian travel time would be negatively correlated with increases in the jaywalking ratio, as jaywalking pedestrians would not have to yield or wait for traffic lights. However, because of the environment design (see figure 3.4), both pedestrian types were only assigned a thin lane to walk on. This caused artificial queues to form and difficulties passing opposing pedestrians in both lanes on both extremes of the jaywalking ratio, as jaywalking pedestrians were not able to walk on the lane of the legal pedestrians and vice versa. This is a clear oversight, and something that can be improved upon in further research. See figure 5.1.

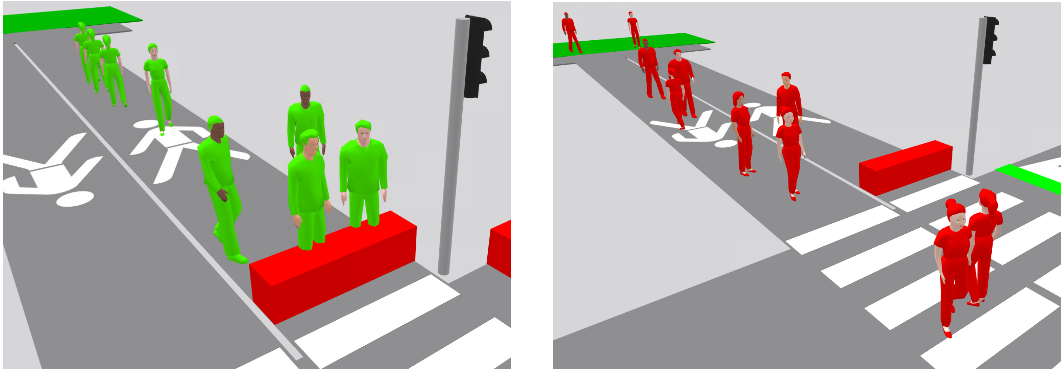

Figure 5.1: Artificial queues start forming and difficulties passing opposing pedestrians occur when the jaywalking ratio is minimised (left) and maximised (right).

5.3 Implications of Findings

This discovery presents significant societal and ethical considerations. On one hand, the potential for reduced travel times may result in diminished urban congestion, decreased emissions, and enhanced transportation efficiency. Such reductions are pivotal in achieving global sustainability objectives, with benefits for both environmental and human health. On the other hand, promoting or tolerating jaywalking could undermine pedestrian and vehicular safety, heightening the likelihood of accidents and injuries [2] [19]. Increased accident frequency from jaywalking can, as a result, also decrease overall traffic flow [20] which could negate possible increases in efficiency from jaywalking.

This scenario prompts a critical evaluation of traffic regulations: whether to prioritise efficiency and potentially streamline transit times or to uphold strict legal standards to ensure public safety and maintain order. When weighing these benefits and risks an important takeaway from our results is that for most vehicle densities ($n \leq 700$) jaywalking ratio had minimal impact on vehicle travel times. As such, the benefits potentially gained from optimising efficiency in these scenarios might not be great enough to consider reducing the safety of pedestrians.

5.4 Limitations

While this study provides valuable insights into the effects of jaywalking on urban traffic dynamics, several limitations should be acknowledged.

Generalisability

Firstly, the simulation environment was constrained to a single street with one traffic light, limiting the generalisability of the findings to more varied urban layouts. More complex traffic environments, incorporating for example multiple lanes, different crossings or multiple roads into the simulation would help make the simulation and it's findings more realistic.

Jaywalking Behaviour

The binary classification of pedestrian behaviour into either jaywalking or legal crossing oversimplifies the nuanced choices pedestrians make based on multiple factors, such as traffic density, personal urgency, propensity and overall jaywalking behaviour. This simplified approach may not capture the full spectrum of pedestrian interactions with traffic, potentially skewing the impact of jaywalking on traffic flow and safety, possibly in both directions.

External Factors

The scenarios did not account for the influence of external factors such as weather conditions or other unexpected events, which can significantly affect both pedestrian behaviour and vehicle traffic. All pedestrians in our simulation walk perfectly, and all vehicles drive perfectly, which will never be the case in the real world.

Safety Analysis

This study did not include simulation or analyses of safety metrics or injury outcomes related to jaywalking and vehicular interactions. Consequently, the implications of jaywalking on pedestrian and traffic safety remain unexplored within these simplified simulation scenarios. It is well established that an increase in jaywalking positively correlates with vehicle-pedestrian conflicts [2] [19], which makes this aspect highly relevant.

5.5 Suggestions for Future Research

Future studies should aim to address the limitations identified in this research and explore additional dimensions to provide a more holistic understanding of the interplay between jaywalking and urban traffic dynamics.

Incorporating Safety Metrics

Future research should include the analysis of safety metrics and injury outcomes related to jaywalking and vehicular interactions. By simulating scenarios that account for collision rates, near-misses, and accident severity, we can better understand the trade-offs between efficiency and safety. This could involve the use of more advanced simulation tools that incorporate pedestrian behaviour models reflecting real-world decision-making and reaction times.

Expanding Urban Layouts and Complexity

To enhance the generalisability of findings, future studies should simulate a variety of urban layouts, including multiple intersections and different traffic control mechanisms. Including other elements such as roundabouts, multi-lane roads, varying signal behaviour, among other things, could provide deeper insights into how jaywalking affects traffic in scenarios that better depict the real world.

Weather and Environmental Factors

Future research should consider the psychological and behavioural aspects of both pedestrians and drivers with more complexity. Understanding jaywalking based on demographic factors, personal urgency and risk perception can help create more realistic models. Additionally, investigating the impact of driver behaviour in combination with pedestrian behaviour, such as aggressive driving or strict compliance with laws, can provide a more nuanced understanding of traffic dynamics from several perspectives.

Real-World Data Integration

This study used data collected in a previous study [18] to define the parameter for pedestrian flow. Integrating real-world data from traffic cameras, sensors and accidents from a specific area can validate simulation models and enhance their accuracy and relevance. As this was only one observational study used, incorporating other sources of data could further increase accuracy and realism. Further extending this methodology to vehicle traffic, by using observational data from traffic cameras etc, could further this further, and is left as suggestions for future work. Collaboration with traffic institutions or municipalities could prove beneficial.

Technological Innovations

The integration of emerging technologies such as autonomous vehicles and smarter traffic signals can transform urban traffic management. Future studies should investigate how these technologies can improve traffic efficiency and mitigate the negative impacts of jaywalking. Simulating scenarios with a mix of traditional and autonomous vehicles can provide insights into future urban design.

By addressing these aspects, future research can provide a more comprehensive understanding of the complex interplay between jaywalking and urban traffic, contributing to the development of safer and more efficient environments.

6 Conclusions

Below is a summary of the entire report, with main findings and takeaways.

6.1 Reflection

This study set out to explore the nuanced effects of jaywalking on urban traffic congestion and vehicle travel times using a simulation approach to model various pedestrian behaviours and vehicle flows. We aimed to answer two key research questions: how varying percentages of jaywalking pedestrians affect vehicle and pedestrian travel times, and how these impacts change with different levels of vehicle flow. This study provides insights into the interplay between jaywalking and traffic dynamics in a specific traffic environment, challenging some previous works and confirming others.

Key Findings

The main findings answering the research questions posed in section 1.3 of the study are the following.

1. **Impact of Jaywalking on Vehicle Travel Times (RQ1 & RQ2):** At lower vehicle flows ($n \leq 700$), the ratio of jaywalking to legally crossing pedestrians had minimal impact on vehicle travel times. At higher vehicle flows ($n \geq 800$), higher jaywalking ratios significantly reduced vehicle travel times. This counter-intuitive result is explained by the decreased use of pedestrian traffic signals at these ratios, which increased green light time for vehicles and reduced overall standstill time.

2. **Impact of Jaywalking on Pedestrian Travel Times (RQ1 & RQ2):** Pedestrian travel times were fastest when the jaywalking ratio was balanced between jaywalking and legal crossings. The difference was small, with an 8% increase when comparing the highest and lowest pedestrian travel time results. This difference is attributed to a design oversight of the simulation environment, explained further in section 5.2 and figure 5.1.

3. **Vehicle Standstill Time:** The standstill time for vehicles appears to increase exponentially with vehicle flow but was significantly lower at higher jaywalking ratios. This indicates that jaywalking, despite its risks, can improve traffic fluidity in simplified scenarios by reducing the frequency of complete stops. This does not take into account the documented increase in accidents related to increases in jaywalking [2] [19].

4. **Comparison to Previous Studies:** These findings challenge prior research that suggests jaywalking generally increases traffic congestion more than legal crossings. This study found that under certain conditions, jaywalking might reduce congestion.

Our finding that high ratios of jaywalking are beneficial for vehicle travel time offers many interesting implications for the interactions between pedestrians and vehicles. Reducing stop time for vehicles in favour of yielding for pedestrians proved detrimental to reducing vehicle travel time, suggesting that signalised crosswalks are not always the optimal solution for traffic flow. Other crossing options which utilise yielding, such as unsignaled crosswalks with pedestrian precedence, could potentially prove a more effective option. Reduction in vehicle travel times reduces urban congestion and emissions and enhances transportation efficiency, thus furthering global development goals whilst also improving the experience for road users.

However, optimising certain aspects of traffic usually comes at the expense of others. Signalised crosswalks are designed for the safety of both pedestrians and vehicles and favouring other options of pedestrian crossing could come at the risk of reduced traffic safety. Promoting or tolerating jaywalking could therefore increase risk for all road users, highlighting the importance of evaluating whether to prioritize efficiency or uphold strict legal standards to safeguard public safety.

6.2 Evaluation of Results

The results of this study are both favourable and cautionary. They highlight the potential efficiency gains from certain jaywalking behaviours in a specific scenario but underline the need for a balanced approach that also prioritises safety. The findings challenge some established beliefs about jaywalking's impact on traffic flow, suggesting that further research is necessary to fully understand these dynamics. The study's aim of using simulation in a controlled environment to isolate specific variables also pointed to limitations inherent with such a simplified approach. Real-world research and more complex simulations are essential next steps to ensure the validity and applicability of these insights.

6.3 Future Work

This thesis offers comprehensive suggestions for future work in section 5.5. These suggestions are given to further future understanding of the dynamic interactions between pedestrians and vehicles, to contribute to safer and more optimised traffic environments.

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Appendix A

Simulation files

Below is the link to a GitHub repository containing all files used in the project.

https://gits-15.sys.kth.se/merland/PTV-Vissim-Traffic-Simulation

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