Master Thesis

Capacity increase through double stops in tram operations

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Acknowledgments

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Abstract

This thesis investigates the capacity increase achieved through the implementation of double stops in tram operations. Despite the recognized potential of double stops to enhance stop capacity, quantitative documentation of their extent is lacking in the literature. The objective of this research is to gain a better understanding of the topic and provide a general approach that can be applied to any tramway network.

To achieve this objective, the key agents operating in stops were identified, and their interactions were analyzed to develop a simulation tool. This tool, implemented in Python, tracks the performance parameters of the network during peak hours. Experiments were conducted in the Vienna Ring case, where single stops were transformed into double stops, and line frequencies were modified to assess the impact on performance parameters.

The results reveal that the Vienna Ring is currently operating at a low utilization factor, with only 33% utilization from an Average Period perspective. However, the maximum utilization factor for single stops is 70%, while double stops can accommodate double that utilization factor at 140%. Furthermore, double stops significantly reduce waiting times by 84% compared to single stops. The "Worst First Dynamic" (WFD) method, in combination with the simulation tool, is identified as the most effective approach for transitioning from single to double stops.

The study concludes that it is advisable to simulate subsets of stops rather than individual stops, as changes in one stop can impact the performance of subsequent stops. The findings of this research contribute to both theoretical and practical perspectives. The theoretical significance lies in shedding light on the double stops concept and improving understanding. From a practical standpoint, the developed simulation tool provides urban planners with a valuable resource for evaluating changes to existing tramway networks and designing new ones.

Keywords: double stops, capacity increase, tram operations, simulation tool, performance parameters, utilization factor, waiting time, Vienna Ring, Worst First Dynamic, urban planning, transportation networks, Python.

Resumen

Esta tesis investiga el aumento de capacidad conseguido mediante la implantación de paradas dobles en las operaciones del tranvía. A pesar del reconocido potencial de las paradas dobles para aumentar la capacidad de las paradas, falta en la literatura documentación cuantitativa sobre su alcance. El objetivo de esta investigación es comprender mejor el tema y proporcionar un enfoque general que pueda aplicarse a cualquier red de tranvías.

Para lograr este objetivo, se identificaron los agentes clave que operan en las paradas y se analizaron sus interacciones para desarrollar una herramienta de simulación. Esta herramienta, implementada en Python, realiza un seguimiento de los parámetros de rendimiento de la red durante las horas punta. Se realizaron experimentos en el caso de la avenida Ringstrasse de Viena, en el que se transformaron paradas simples en paradas dobles y se modificaron las frecuencias de las líneas para evaluar el impacto en los parámetros de rendimiento.

Los resultados revelan que la avenida Ringstrasse de Viena funciona actualmente con un factor de utilización bajo, con sólo un 33% de utilización desde la perspectiva del Periodo Medio. Sin embargo, el factor de utilización máximo para las paradas individuales es del 70%, mientras que las paradas dobles pueden duplicar ese factor de utilización con un 140%. Además, las paradas dobles reducen significativamente los tiempos de espera en un 84% en comparación con las paradas simples. El método "Worst First Dynamic" (WFD), en combinación con la herramienta de simulación, se identifica como el método más eficaz para la transición de paradas simples a paradas dobles.

El estudio concluye que es aconsejable simular subconjuntos de paradas en lugar de paradas individuales, ya que los cambios en una parada pueden repercutir en el rendimiento de las paradas siguientes. Los resultados de esta investigación contribuyen a las perspectivas teórica y práctica. La importancia teórica radica en que arrojan luz sobre el concepto de paradas dobles y mejoran su comprensión. Desde un punto de vista práctico, la herramienta de simulación desarrollada proporciona a los planificadores urbanos un valioso recurso para evaluar los cambios en las redes de tranvía existentes y diseñar otras nuevas.

Keywords: paradas dobles, aumento de capacidad, operaciones de tranvía, herramienta de simulación, parámetros de rendimiento, factor de utilización, tiempo de espera, Vienna Ring,Worst First Dynamic, planificación urbana, redes de transporte, Python.

Chapter 1

Resum

Aquesta tesi investiga l'augment de capacitat aconseguit mitjançant la implantació de parades dobles a les operacions del tramvia. Malgrat el reconegut potencial de les parades dobles per augmentar la capacitat de les parades, manca a la literatura documentació quantitativa sobre el seu abast. L'objectiu d'aquesta investigació és comprendre millor el tema i proporcionar un enfocament general que es pugui aplicar a qualsevol xarxa de tramvies.

Per assolir aquest objectiu, es van identificar els agents clau que operen a les parades i se'n van analitzar les interaccions per desenvolupar una eina de simulació. Aquesta eina, implementada a Python, fa un seguiment dels paràmetres de rendiment de la xarxa durant les hores punta. Es van fer experiments en el cas de l'avinguda Ringstrasse de Viena, en què es van transformar parades simples en parades dobles i es van modificar les freqüències de les línies per avaluar l'impacte als paràmetres de rendiment.

Els resultats revelen que l'avinguda Ringstrasse de Viena actualment funciona amb un factor d'utilització baix, amb només un 33% d'utilització des de la perspectiva del període mitjà. Tot i això, el factor d'utilització màxim per a les parades individuals és del 70%, mentre que les parades dobles poden duplicar aquest factor d'utilització amb un 140%. A més, les parades dobles redueixen significativament els temps d'espera un 84% en comparació de les parades simples. El mètode "Worst First Dynamic" (WFD), en combinació amb l'eina de simulació, s'identifica com a mètode més eficaç per a la transició de parades simples a parades dobles.

L'estudi conclou que és aconsellable simular subconjunts de parades en comptes de parades individuals, ja que els canvis en una parada poden repercutir en el rendiment de les parades següents. Els resultats de la investigació contribueixen a les perspectives teòrica i pràctica. La importància teòrica és que donen llum sobre el concepte de parades dobles i milloren la seva comprensió. Des d'un punt de vista pràctic, l'eina de simulació desenvolupada proporciona als planificadors urbans un valuós recurs per avaluar els canvis a les xarxes de tramvia existents i dissenyar-ne de noves.

Keywords: parades dobles, augment de capacitat, operacions de tramvia, eina de simulació, paràmetres de rendiment, factor d'utilització, temps d'espera, Vienna Ring, Worst First Dynamic, planificació urbana, xarxes de transport, Python.

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Chapter 2

Introduction

2.1 Opening

Tramway networks have long played a vital role in the transportation infrastructure of numerous cities across the world, particularly in Europe. Their ability to efficiently move large volumes of passengers within urban environments has made them a preferred mode of public transportation. With the growing demands of urbanization and the increasing need for sustainable mobility solutions, the significance of tramways has only intensified. As cities strive to address congestion, reduce emissions, and enhance transportation accessibility, exploring innovative strategies to optimize the capacity and efficiency of tram operations becomes imperative. This thesis delves into one such strategy – the utilization of double stops – as a means to augment capacity and enhance the performance of tramway networks.

Double stops refer to a specific operational technique employed in tram systems. Traditionally, tram stops are located at regular intervals along a tramway line, allowing passengers to board or disembark the tram. In contrast, double stops are characterized by the provision of two adjacent spaces in close proximity to each other where the tram can stop. This arrangement allows two trams to stop simultaneously at the same stop, serving as an effective means to increase passenger capacity without compromising on schedule adherence or operational efficiency. By facilitating the boarding and alighting of passengers from multiple doors simultaneously, double stops have the potential to reduce dwell times and streamline the flow of passengers, thereby maximizing the overall capacity of the tramway system. The incorporation of double stops presents a promising avenue for enhancing the efficiency and effectiveness of tram operations, offering a potential solution to the challenges posed by increasing ridership and limited infrastructure capacity.

2.2 Background and Context

The field of urban mobility and public transportation has garnered significant attention in recent years, leading to numerous studies focusing on various aspects of tramway networks. These studies have shed light on the agents involved in the operation of tram stops, their characteristics, and the implications they have within the broader context of a public transport network. Additionally, research has explored the different types of tram stops and their potential situational implications. Moreover, a notable distinction emerges when it comes to analyzing tram stops, namely the use of steady formulas or the design of simulations to evaluate their effectiveness and performance. These aspects, along with other relevant topics, will be comprehensively discussed and analyzed in the forthcoming literature review chapter.

Several studies have extensively examined the agents present in tram stop operations. These agents include tram operators, passengers, and traffic regulators, each playing a crucial role in the overall functioning of a tramway system. The characteristics and behaviors of these agents have been described and analyzed, with a particular focus on their interactions and the impact they have on the overall efficiency and capacity of the tram network. Understanding the dynamics of these agents is crucial for the effective design and management of tram stops, as it allows for the identification of potential bottlenecks, congestion points, and areas requiring optimization.

In addition to examining the agents, previous research has delved into the categorization and typology of tram stops. The suitability of each type of stop has been explored in various circumstances, taking into account factors such as passenger demand, location, available space, and infrastructure constraints. By understanding the characteristics and implications of different stop types, urban planners and transportation authorities can make informed decisions regarding the appropriate choice and deployment of tram stops within a network.

Furthermore, two distinct approaches have emerged when studying tram stops: the utilization of steady formulas and the development of simulations. Steady formulas involve the application of mathematical equations and analytical models to evaluate the capacity and performance of tram stops. These formulas provide valuable insights into the fundamental characteristics and limitations of stops, but they often simplify real-world complexities and may not fully capture the dynamic nature of tram operations. On the other hand, simulations offer a more comprehensive and dynamic analysis by creating virtual environments to replicate tram operations. Simulations enable researchers to explore different scenarios, assess the impact of varying parameters, and identify optimal solutions for stop design and management. Both approaches have their merits and limitations, and the choice between them depends on the research objectives and available data.

In the upcoming literature review chapter, these various aspects, including the role of agents, types of tram stops, and the steady formulas versus simulation approaches, will be critically examined. The chapter will provide a comprehensive overview of the existing research in the field, highlighting the gaps, controversies, and unresolved questions that form the basis for the present study. By synthesizing and analyzing the available literature, this research aims to contribute to a deeper understanding of the capacity increase potential through the implementation of double stops in tram operations

2.3 Problem Statement

The problem at hand revolves around the limited understanding of the quantitative impact of double stops on the performance of tramway networks. While double stops are commonly implemented in numerous tramway systems worldwide with the aim of enhancing stop and network performance, there is a dearth of comprehensive documentation that quantifies the extent of this enhancement. Existing research on the topic predominantly takes a qualitative approach, lacking a thorough quantitative analysis of the benefits brought about by double stops. Consequently, a significant gap persists in determining the precise extent to which double stops contribute to improving the performance of a tramway network.

This research aims to bridge the existing gap by undertaking a systematic and comprehensive investigation into the quantitative impact of double stops on tramway network performance. By employing empirical data collection methods and utilizing appropriate analytical techniques, this study seeks to quantify the specific enhancements brought about by the implementation of double stops. By doing so, the research will provide valuable insights into the magnitude of improvement in terms of overall efficiency of tramway operations.

2.4 Objectives and Research Questions

This study is guided by the following specific objectives and research questions:

- To identify the main agents that define a public transport tramway network, analyze their interactions, and develop a simulation framework for their implementation.

  The first objective focuses on understanding the key agents involved in the operation of a public transport tramway network. This includes tram operators, passengers, and traffic regulators, whose interactions play a crucial role in the overall functioning of the network. The research questions associated with this objective revolve around the identification of these agents, their interactions with each other, and the development of a simulation framework that accurately models their behaviors and dynamics

- To define and describe the key performance parameters of a tramway network.

  The second objective aims to define and describe the essential performance parameters that measure the effectiveness and efficiency of a tramway network. The research questions in this objective focus on determining the specific performance parameters, quantitatively defining and measuring them, and understanding the factors that influence their values within the context of tramway operations.

- To design experiments utilizing a simulation framework that quantify the impact of double stops on the key performance parameters of a tramway network.

  The third objective centers on the impact of double stops on the identified key performance parameters of a tramway network. Through experiments designed within a simulation framework, this objective aims to quantify the specific changes observed in the performance of the tramway network when double stops are implemented. The research questions associated with this objective seek to understand the effects of double stops on the key performance parameters and determine if their impact can be quantitatively measured and compared against the baseline performance.

- To develop a methodology that enables the fulfillment of the research questions and objectives in a general approach, applicable to tramway networks in different cities.

  The fourth objective focuses on developing a methodology that can address the research questions and achieve the stated objectives in a general approach. While the methodology will be tested in a particular tramway network, the one in Vienna, its purpose is to be applicable to tramway networks in other cities as well. The research questions associated with this objective aim to determine how a comprehensive and adaptable methodology can be formulated, tested in a specific case study, and transferred to tramway networks in different urban contexts.

By pursuing these objectives and answering the corresponding research questions, this study aims to contribute to a deeper understanding of tramway network operations, the effects of double stops, and the development of a practical and transferable methodology for optimizing tramway operations in various cities.

2.5 Significance and Motivation

Research in the field of urban mobility, particularly in relation to tramway networks, is of utmost importance due to its direct impact on transportation challenges faced by cities globally. Efficient urban mobility plays a vital role in sustainable development and the overall quality of life for residents. Tramway networks are recognized as effective solutions within urban areas, and this research aims to enhance their capacity and efficiency through the implementation of double stops. By quantitatively assessing the impact of double stops on key performance parameters, this study provides valuable insights for urban planners and policymakers, contributing to the design and optimization of tramway networks. Additionally, the development of a transferable methodology expands the applicability of the research, enabling its utilization in diverse urban contexts and promoting best practices in tramway operations worldwide. Ultimately, this research enhances our understanding of tramway network performance and contributes to the advancement of sustainable urban mobility.

2.6 Scope and Limitations

The scope of this study involves the construction and utilization of a simulation model to address the research questions and objectives established. However, it is important to acknowledge that simulations inherently involve a trade-off between resemblance to reality and the associated costs of development and execution. Therefore, the simulation model will rely solely on publicly available data to define its parameters and the depth of analysis will be constrained by the availability of data.

Furthermore, while the simulation model and experiments have the potential to be applicable to tramway networks of various sizes and configurations, the focus of this study will be on the Vienna Ring, which is a subset of the larger Vienna Tramway Network. This selection is made based on the particular significance and relevance of the stops within the Vienna Ring. The results obtained from this specific case study will provide valuable insights and may have implications that can be extrapolated to other tramway networks.

Additionally, it is important to acknowledge that this study is limited by the availability and quality of data. The simulation model and experiments will rely on publicly accessible data sources, which may have certain limitations and may not capture the complete intricacies of the tramway network and its operations. Despite these limitations, this study strives to provide valuable insights and contribute to the understanding of the impact of double stops on tramway network performance, within the confines of the available data and the specific context of the Vienna Ring.

2.7 Organization of the Thesis

This thesis is organized into several chapters that collectively contribute to the understanding and analysis of the capacity increase through double stops in tram operations. The structure of the thesis is as follows:

- Literature Review. In this chapter, the relevant literature and theories related to the field of study are reviewed. The context of the problem being addressed is established, and previous research on urban mobility, tramway networks, and the use of double stops is examined. The chapter also identifies any gaps or controversies in the existing literature that motivate the research.

- Modeling the Simulation. This chapter delves into the details of modeling the simulation used in the study. It describes the data sources, parameters, and variables used in the simulation. Additionally, the interactions between different agents within the tramway network are defined and explained. The general structure and functioning of the simulation model are outlined, providing insights into how the simulation represents the real-world tram operations.

- Simulation Experiment and Analysis. Building upon the developed simulation model, this chapter focuses on conducting experiments to address the research questions and objectives. The chapter describes the design of the experiments, including the scenarios and variations tested. The analysis of the simulation results is presented, quantifying the impact of double stops on key performance parameters and providing insights into the behavior and efficiency of the tramway network.

- Conclusions. The final chapter of the thesis summarizes the methodologies used, restates the key findings, and discusses their implications. The chapter also highlights the limitations of the study and identifies areas for future research and development. This chapter concludes by providing a comprehensive overview of the research and its contributions to the field of capacity increase through double stops in tram operations.

By following this structure, the thesis provides a coherent and logical progression of ideas, starting from the introduction and background, reviewing the relevant literature, developing a simulation model, conducting experiments, and concluding with a discussion of the findings and suggestions for further research.

Chapter 3

Literature Review

The literature review serves the purpose of comprehending the scientific context surrounding the topic of capacity increase through double stops in tram operations. By delving into prior studies, articles, and relevant literature, a thorough understanding of the existing body of knowledge on this subject can be achieved.

This literature review aims to critically analyze and synthesize previous research, shedding light on the potential of double stops to enhance tram capacity. Through a systematic approach, empirical studies, theoretical frameworks, and practical applications pertaining to double stops in tram operations will be examined. This review intends to identify achievements, limitations, and research gaps within the current scholarly discourse, contributing to the advancement of knowledge in this field.

To accomplish this, rigorous search strategies will be employed, ensuring a meticulous analysis of relevant publications. Furthermore, a critical evaluation of findings will be conducted, drawing upon diverse disciplines such as transportation engineering, urban planning, operations research, and related fields to facilitate a comprehensive examination.

3.1 Public transport stop agents

To conduct any analysis of public transport qualities, it is imperative to have a clear understanding of the components that comprise the system, their interdependence, and priorities. For this particular thesis, which centers on analyzing public transport stops, we first outline the components that constitute such stops [1]:

- Stopping area: The designated spot where public transport vehicles, such as buses and train cars, come to a halt.
- Platform: The location where passengers wait for vehicles and alight and board. While at bus stops, the platform is typically a part of the sidewalk, at train stations, it is a separate space constructed for passengers' use.
- Berth: Each stop area includes at least one berth, though some may have several. A berth refers to the area occupied by a public transport vehicle. The number of berths per stop area can be increased to boost stop capacity, as will be elaborated later. Nevertheless, deploying more than three berths ceases to be efficient.

Hence, a transit stop can be perceived as a queuing system that manages the flow of transit vehicles and passengers. Passengers and vehicles typically exhibit distinct arrival distributions at a station. While passengers tend to follow inter-arrival distributions, such as exponential distributions, vehicles adhere to headway distributions, which may be uniform, for example.

Due to these variations, vehicles must pause at the stop to allow passengers to alight and board, thereby incurring a "Passenger Service Time" (PST), contingent upon the number and characteristics of waiting passengers. If another vehicle arrives while this process is underway, in the case of a one-berth-stop, it must wait for the preceding vehicle to depart before passengers can alight and board, resulting in an "Average Waiting Time" (AWT). To reduce time spent in this scenario, multiple-berth-stops are constructed to enable more than one vehicle to accommodate passenger alighting and boarding simultaneously.

3.2 Design of stops

3.2.1 Type of stops

In Vienna, the majority of the stops are designated as request stops, indicating that the vehicle will only halt if a passenger explicitly requests the stop or if there is a passenger waiting at the stop. Nevertheless, it is noteworthy that there is typically a passenger present, thereby ensuring that the tram is highly likely to stop regardless [2]. Tram stops can either be separated from traffic with an independent track or located in areas with the risk of being blocked by other vehicles. As such, a useful classification of tram stop types is as follows [3]:

- Type I – single tram stops with one stopping-space in the middle of the street, where alighting and boarding occurs in conjunction with other vehicles. This arrangement increases the possibility of other vehicles obstructing the tram track.
- Type II – single tram stops only for trams, with one stopping-space located on a separate track, where the passenger platform is directly adjacent to the track. This arrangement minimizes the impact of other vehicles on tram traffic.
- Type III – tram stops with two stopping-spaces located in the middle of the street, where alighting and boarding occurs in conjunction with other vehicles. This arrangement increases the possibility of other vehicles obstructing the tram track, as well as reciprocal tram blockages.
- Type IV – double tram stops only for trams, with two stopping-spaces located on a separate track, where the passenger platform is directly adjacent to the track. This arrangement minimizes the impact of other vehicles on tram traffic, but reciprocal tram blockages may occur.
- Type V – double tram and bus stops, with two stopping-spaces located on a separate lane for trams and buses. The passenger platform is directly adjacent to the tram-bus lane. This arrangement minimizes the impact of other vehicles on both tram and bus traffic, but reciprocal tram and bus blockages may occur. This type of stop is employed only in cases where trams and buses share separate lanes.

A visualization of the five types of tram stops can be seen in Figure 3.1.

In [3], a statistical analysis was conducted to examine the time lost in the specific case of Krakow. The results showed that there was no significant difference in Average Waiting Time between double stops located in the middle part of the street and separated double common tram-bus stops (Types III and V), as well as Types I and II. However, a significant difference was found when comparing the distributions of the remaining three cases (Type I and II, Type III and V, and Type IV) with a confidence level of 95%. This confirms the importance of classifying and considering the type of stop.

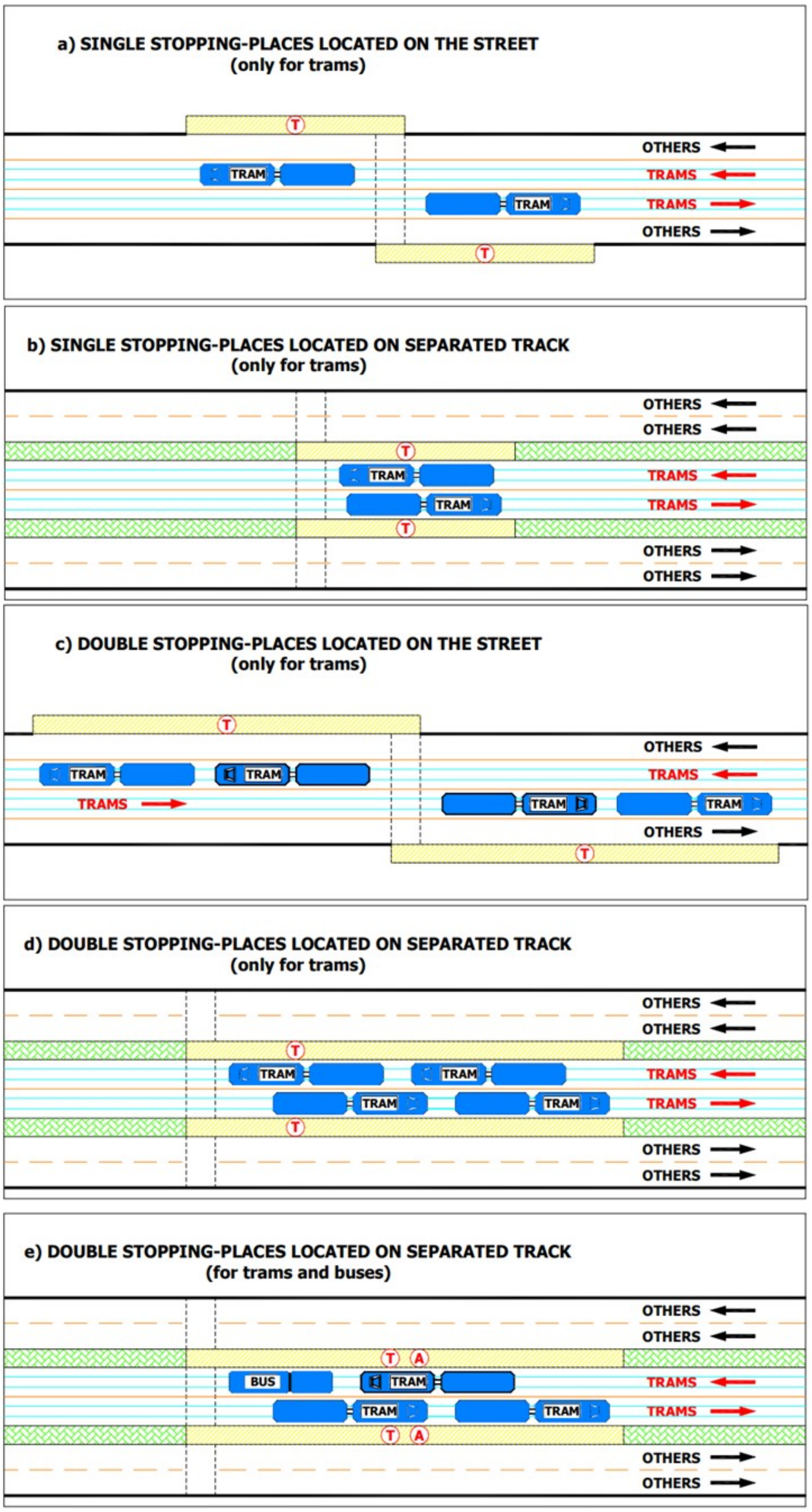

Fig. 3.1: Scheme of types of tram stops from [3]

3.2.2 Stop location

3.2.2.1 Micro location

Various types of tram stops can be located in a number of ways. They may be situated in close proximity to the nearest intersection if the stop is within range of that intersection, or alternatively, they may be located mid block if the distance to the nearest intersection is significant. Tram stops may also be positioned near the near side or far side of the nearest intersection. The type of neighboring intersection is an important consideration, particularly with regard to whether it is a signalized or non-signalized intersection. When tram stops are located near side signalized intersections, it is worth considering whether trams have priorities in traffic lights. In summary, there are six principal possibilities for locating tram stops in relation to the nearest intersection [3].

- Location I - the tram stop is located at a far side signalized intersection. Figure 3.2 in a) section.
- Location II - the tram stop is situated at a near side signalized intersection, and trams do not have traffic light priorities. Figure 3.2 in a) section.
- Location III - the tram stop is located at a near side signalized intersection, and trams have traffic light priorities (i.e. the green signal is given to the vehicle that has finished alighting and boarding passengers).
- Location IV - the tram stop is positioned at a far side non-signalized intersection. Figure 3.2 in b) section.
- Location V - the tram stop is situated at a near side non-signalized intersection. Figure 3.2 in b) section.
- Location VI - the tram stop is located mid block, at a significant distance from nearby intersections. Figure 3.2 in c) section.

The analysis [3] was conducted following the methodology described in Figure 3.2. The study examined the amount of time lost across various locations, and found that stops located near side signalized intersections without priority for trams (Location II) differed from the mean values observed at other locations. As a result, only this case warrants distinction, while the remaining locations can be considered equivalent.

3.2.2.2 Macro location

Another important way of classifying tram stops is based on their location in relation to various parts of the city. Traffic conditions can vary significantly between different areas of the city, such as the close old city area with partial restrictions for private cars, the wide city centre, and the remaining areas of the city. However, this classification should be treated with caution, as it has a general character. Three possibilities of stop locations in relation to the zone of the city are proposed for the city of Krakow as follows [3]:

- Zone I - close city centre, all stops are located inside the first ring (including stops on the perimeter of the first ring). This zone is characterized by a high density of intersections and relatively short stopping spaces. There may also be restrictions for selected groups of vehicles.

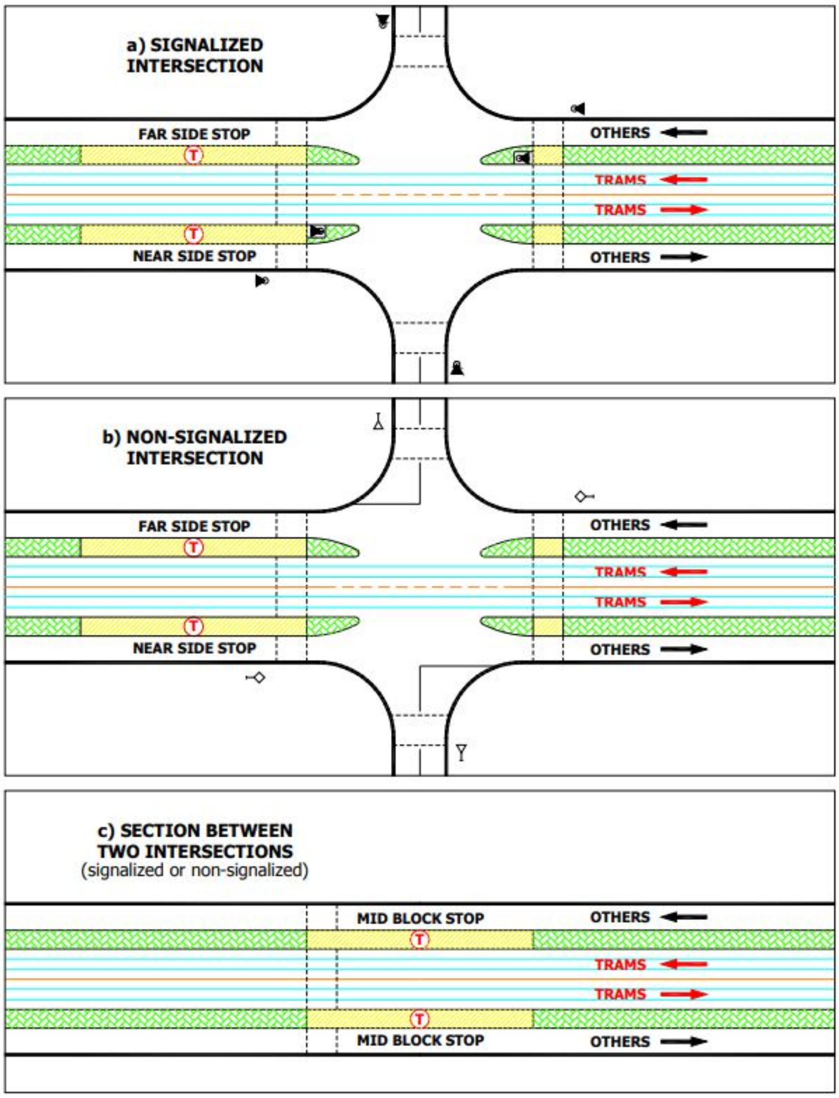

Fig. 3.2: Schemes of possible tram stop's locations from [3]

- Zone II - wide city centre, tram stops are located between the first and second ring (including stops on the perimeter of the second ring). This zone is characterized by larger stopping spaces and a lower density of intersections.
- Zone III - tram stops located outside the city centre (outside the second ring). This zone is characterized by large stopping spaces and a small density of intersections.

In a manner consistent with the approach used in prioritized sections, a Mann-Whitney test was performed to evaluate whether there were any significant differences in the distributions of time lost for stops located in the narrow and broad city center (Zones I and II). The results indicate that no such differences exist. However, in contrast, the distribution of time lost for stops situated outside the city center (Zone III) significantly differed from the other locations. Therefore, this distinction may be considered as the most significant finding of this study.

3.2.3 Steady formula

In the literature, two methods of modeling stop capacity have been documented. The first approach employs analytical deterministic models that aim to estimate capacity using a steady-state formula, with the most renowned being the Highway Capacity Manual [1]. The second approach entails employing simulation models to calculate not only the capacity but also other critical performance indicators for stop operations. However, a detailed discussion of this approach will be presented in subsequent sections.

According to previous research, travel time can be decomposed as demonstrated in Equation 3.1.

$$T_t = T_m + T_j + T_s \tag{3.1}$$

T_t: total travel time along the route or section of a route
T_m: total time spent in movement
T_j: total time delayed at junctions
T_s: total time spend at bus stops

The overall time spent in motion relies on the length of the route or section of route (L) and the corresponding running speed (V_r). The total time spent delayed at junctions is dependent on the mean delay at junctions (d_j) - assumed equal at all junctions for simplicity - and the number of junctions (N_j) along the route. The total time spent at bus stops is dependent on the mean stopping delay (d_s) - also assumed equal at all bus stops - and the number of stops on the route (N_s). Therefore, Equation 3.1 can be expressed as Equation 3.2.

$$T_t = \frac{L}{V_r} + N_j d_j + N_s d_s \tag{3.2}$$

If there is low demand, vehicles may not stop, resulting in negligible average delay at each stop. Similarly, if accessibility along the route is poor, the number of stops on the route will be low. In either scenario, the third term of Equation 3.2 will have minimal impact on the total time.

However, as demand and accessibility increase, the time spent at a stop becomes increasingly important. The delay experienced at a stop is typically made up of two components: passenger transference (d_p) and congestion in the stop area (d_c). Thus, the overall stopping delay (d_s) can be expressed as $d_s = d_p + d_c$.

Under moderate demand conditions, the likelihood of congestion at bus stops is typically low, resulting in a low value of dc. However, as tram flow increases, the value of d_c also increases, leading to extra delays and potential queues at the stop. Meanwhile, d_p refers to the alighting and boarding processes, which can be optimized to reduce the time lost at a stop.

At times, the increase in flow and demand may be caused by short-term peaks resulting from the combination of tram schedules from various routes, traffic conditions, and batch passenger arrivals. This scenario is particularly common in main streets, town centers, and areas near other public transport vehicle stops, where demands and flows are not constant. Thus, the physical and operational design of bus stops is crucial in reducing both d_p and d_c.

In summary, priority should be given to link protection, which reduces travel time by protecting vehicles from other traffic; junction priority, which reduces delay by allowing vehicles to pass through junctions easily; and stop priority, which reduces stopping delay by providing appropriate bus stops.

3.2.4 Designing the stop

The underlying design principle of stops is to establish an efficient interchange mechanism that minimizes the service times for both passengers and vehicles. In this regard, a structured design process has been identified in [4], as referred to in the following stages: diagnosis of services, determination of stop spacing, decision on stop type, resolution of stop locations, and assessment of the scheme.

3.2.4.1 Diagnosis of services

The evaluation of transportation services should rely on objective criteria pertaining to mobility. This necessitates an assessment of issues such as accessibility to services, accessibility to vehicles, and movement within these vehicles. To elucidate the fundamental concepts of mobility in [5], a visual approach, Figure (3.3), was developed. In this approach, mobility is considered as the "ease of reaching activities", which is a function of the distance to those activities, as a rough approximation. Three modes of transport, namely walk, bus, and car, are considered, and three regions are identified.

To the left of point A, the objective is to ensure good pedestrian mobility to reach activities. Between points A and B, the aim is to improve accessibility and access to the bus system to enhance people's mobility. To the right of point B, the car would be more attractive unless the movement of the bus system can be improved by increasing its speed. This can be achieved through the implementation of junction and link priorities.

The first variable to be analyzed is the commercial speed. If the commercial speed is less than 20 km/h, or the peak/off-peak variation exceeds 20%, a detailed study of its components should be conducted to determine the causes. If the cruise speed is less than 30 km/h, it indicates a problem in the links between junctions or stops. This issue can be addressed by improving the road surface or by adding link priorities. Conversely, if there are more than four stops per kilometer, regardless of the reason, the causes of this frequency should be investigated. Finally, if the duration of any stop exceeds 15 seconds, the question to be asked is where these delays are originating to direct the priorities. Therefore, the outcome of the analysis is an identification

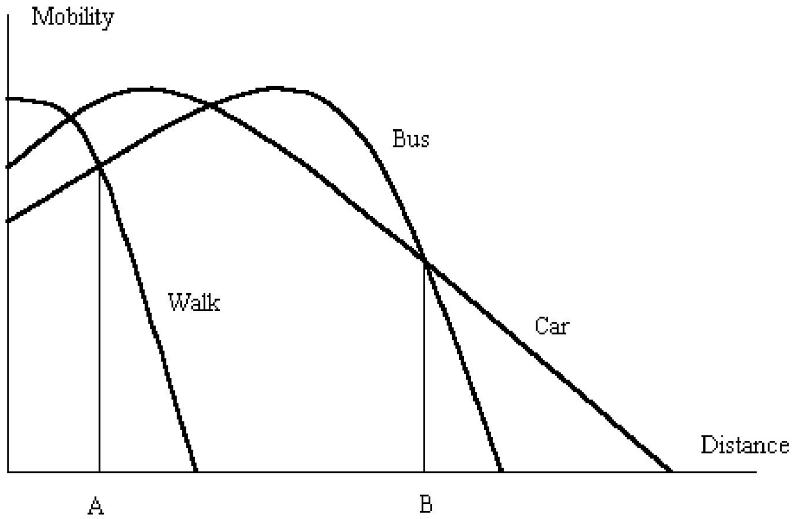

Fig. 3.3: Mobility Diagram from [5]

of the main problems in the corridor concerning the movement of public transport vehicles: at junctions, bus stops, or in the links.

3.2.4.2 Stop spacing

There are at least three significant impacts associated with the location of a bus stop in a given area. These include the accessibility time of passengers to the bus stop, the delay experienced by in-vehicle passengers as a result of the stop, and the operation cost of stopping at the stop. To minimize the aggregate effect of these impacts, an adequate spacing is required. The determination of the stop spacing necessitates the consideration of specific data. These data include passenger density, which is the number of passengers boarding and alighting per hour per kilometer during the critical period, and vehicle flow, which is the number of buses passing through the corridor during the same period. Other variables and parameters must also be considered to estimate the cost-related terms. Although formulas have been used in the literature to compute this distance, they are not applicable in this particular context.

3.2.4.3 Type of stops

The decision regarding the number of stop points - if multiple stops are required - and the number of berths at each stop point is crucial and depends on the capacity required to accommodate stopping vehicles during boarding and alighting operations, minimizing queues and delays. To achieve this goal, it is necessary to estimate the capacity of the stops and determine the corresponding degree of saturation, which is the flow to capacity ratio that ensures an optimal operation.

Several factors need to be considered when estimating bus stop capacity, including the number of linear berths needed for a single bus stop. One approach for determining the number of berths is provided by [1]. For example, the following formula can be used:

$$N_b' = \frac{B(\beta_b p_b + t_c)}{3600 R p_b u} \tag{3.3}$$

N_b': number of berths spaces at a stop
B: boarding demand at the stop (pass/h)
β_b: boarding time per passenger (sec/pass)
p_b: boarding passengers per vehicle in the 15-min peak
t_c: clearance time between successive vehicles (sec)
R: reductive factor to compensate for dwell time and arrivals variations. Normally $R = 0.833$
u: berth utilisation factor

According to [6], the number of stopping points should ensure that the level of saturation is less than 0.4. However, [4] suggests a range between 0.35 and 0.65. Subsequent research has concluded that the practical degree of saturation should not be greater than 0.6, as discussed in [7].

3.2.4.4 Stop location

There are several factors to consider when making a decision about the final location of bus stops. [4] proposed a set of criteria which include maintaining appropriate spacing, placing the stops as close as possible to the demand points, and utilizing available street space. Therefore, determining the exact location and layout of each bus stop is necessary.

Furthermore, designing pedestrian paths to link the stops with the demand points is essential to ensure a high level of accessibility. The final layout of the stop will be determined by the available space and accessibility needs.

Parallel platforms are an effective way to locate multiple bus stops in close proximity while maintaining their independent functionality. Alternatively, sequential stop points can also be used. However, it is important to note that each bus stop location presents a unique problem, and there are few general recommendations that can be made regarding this matter.

3.2.4.5 Assessment of the scheme

The technique used to assess commercial speed relies on an exponential correlation between the frequency of stops and the commercial speed of buses, as shown in [4]. Equation 3.4 below depicts an extension of this methodology:

$$V_c = V_o \cdot e^{(\alpha F_s + \beta F_j)} \tag{3.4}$$

V_c: average commercial speed on a section (km/h)
F_s: frequency of stops for bus stop operations (stop/km)
F_j: frequency of stops for junction operations (stop/km)
V_o, α, β: parameters of calibration

It is important to consider that commercial speed, denoted by Vc, encompasses delays caused by various factors.

Equation 3.4 can be calibrated both before and after the implementation of any adjustments. The "before" parameters can be employed to predict the new commercial speed resulting from a change in the stop frequency due to any cause. The "after" parameters, on the other hand, can be utilized to examine alterations in behavior.

3.3 Modelling stop capacity

3.3.1 Simulation models

The methods and techniques discussed hitherto rely on steady-state formulas, which furnish valuable insights but fall short of accuracy when scrutinizing detailed research, and certain analyses cannot be conducted using this approach. Consequently, a second methodology exists, which involves employing simulation models to determine the capacity and other performance measures of stop operations. The literature offers two simulation models designed explicitly for stop operations: IRENE [8] and PASSION [9]. In reality, PASSION was formulated to surmount some of the limitations of IRENE, which primarily include the lack of consideration given to passenger impacts, such as waiting times and platform density, and the inflexibility in using specific arrival patterns of buses and passengers at the bus stop, such as scheduled bus arrivals or batch arrivals of passengers. The subsequent section outlines a brief summary of the development of PASSION [10].

3.3.2 A real case - PASSION

PASSION (PArallel Stop SimulatION) is a simulation model created to examine the interactions among buses, passengers, and traffic at bus stops. During the initial stages of its development, the intention was to model each section of the bus stop individually: the platform, the stop area, and the exit area. Each of these elements interacts with one another and receives different incoming inputs. Buses from various routes arrive at the stop area following specific schedules, passengers arrive at the platform, and the exit area may be congested with traffic from the surrounding region. The interaction between the stop area and the platform, as well as between the stop area and the exit area, produces a system of queues and delays for buses, as well as waiting times and platform density for passengers. The interaction scheme among the bus stop's agents is presented in Figure 3.4

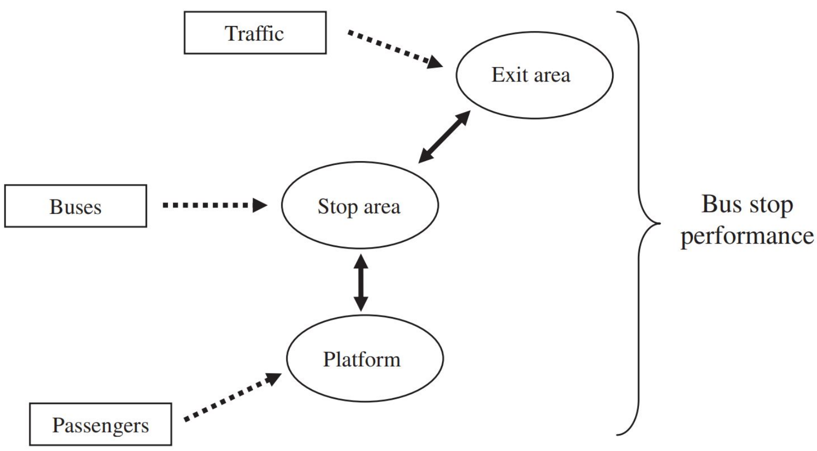

Fig. 3.4: Parallel conception of a bus stop from [10]

3.3.2.1 Structure of the model

The model comprises five primary components: the passenger module, the bus module, the exit module, the interaction model, and the performance module.

The bus module generates the arrivals and attributes of buses. Some of these arrivals can be produced using statistical distributions, while others must be directly entered into the input file. This module also provides other bus characteristics, such as the route number, the quantity of alighting passengers, the average alighting time per passenger for each route, the spare capacity of each arriving bus, and any blocking time for each bus to depart from the stop area.

Similarly, the passenger module generates the arrival and attributes of passengers. The inter-arrival pattern can be created either by using statistical distributions or a spreadsheet. The module also provides passenger characteristics, such as the average boarding time for all passengers or individual values that differentiate them by payment method, age, type of vehicle boarded, and so on.

The exit module controls how vehicles leave the stop area, considering four options:

- Free exit: once the bus has completed the boarding and alighting operations can leave the stop without any delay.
- Traffic signal controls the exit from the stop area: if the signal is red at the departing moment of the bus an extra delay is added until the signal turns green.
- A bus has to re-enter the traffic stream from the stop area: a gap-acceptance process is simulated by data introduced by the user, such as the flow on the adjacent lane, its saturation…
- Any blockage ahead produced by other vehicles: the program processes the blocking times defined in the input file.

free exit, traffic signal control, re-entry into the traffic stream from the stop area, and any blockage ahead caused by other vehicles.

The interaction model organizes the input data, calculates the bus flow and passenger demands, estimates effects on buses and passengers, and computes performance indices for the bus stop.

Finally, the performance module of PASSION calculates the capacity, queues, and delays at the bus stops, as well as the average passenger waiting time and the number of waiting passengers at the platform. PASSION calculates the capacity of a one-berth stop in buses per hour using the expression shown in Equation 3.5. For multiple-berth stops, the same equation can be applied to the last berth of the stop area, which controls the entrance to the bus stops and, therefore, the capacity of the entire stop.

$$Q_b = \frac{3600 N_b}{\sum_{i=1}^{N_b}(t_c + PST_i + t_{ei})} \tag{3.5}$$

Q_b: buses per hour (buses/h)
N_b: number of simulated buses
PST_i: the Passenger Service Time of bus i (s)
t_c: the clearance time between successive buses (s)

t_{ei}: any extra delay within the stop area of bus i (s)

The most important element of capacity is the Passenger Service Time (PST), which is calculated using the rule presented in Equation 3.6 for each bus.

$$PST_i = \beta_0 + \left(\sum_{j=1}^{Pb_i} \beta_{bj} + \beta_{ai} Pa_i \right) \tag{3.6}$$

β_0: average dead time per stop (s)
β_{bj}: boarding time of each passenger (s)
β_{ai}: average passenger alighting time of the bus (s/pass)
Pb_i: number of boarding passengers
Pa_i: number of alighting passengers

The performance module of PASSION calculates various key performance measures. These include:

- The degree of saturation (X_b), which indicates how busy the stop area is and is calculated as $x_b = q_b/Q_b$, where q_b is the total bus flow during the simulation period.
- The mean queue length upstream of the stop area (Lq) is also calculated using the equation:

$$L_q = \sum_{i=1}^{N_b} \frac{L_{qi} d_{qi}}{T} \tag{3.7}$$

L_{qi}: number of buses in queue found by bus i (bus)

d_{qi}: time in queue experimented by bus i (s)

T: simulation period (s)

- The delay to buses (D) is another important performance measure, and it represents the mean delay experienced by a bus due to various factors such as delay in an upstream queue or delay due to boarding and alighting passengers. It is measured in (s/bus).

$$D = \sum_{i=1}^{N_b} \frac{d_i}{N_b} \tag{3.8}$$

d_i: delay of a bus i for any cause (s)

- The average waiting time (AWT), which describes the level of service of a public transport system, is obtained using the equation:

$$AWT = \frac{\sum_{j=1}^{N_p} w_j}{\sum_{i=1}^{N_b} k_{pi}} \tag{3.9}$$

w_{ji}: waiting time of the passenger j (s)

k_{pi}: number of passengers on the platform when the bus i arrives (pass)

N_p: number of passengers present in the simulation

- Additionally, the mean number of passengers on the platform when a bus arrives (Kp) is calculated as an approximation of the platform density.

$$K_p = \sum_{i=1}^{N_b} \frac{k_{pi}}{N_n} \tag{3.10}$$

3.3.2.2 Calibration and validation

A calibration and validation of the PASSION model was conducted for a bus stop located in Santiago, Chile. The data collection method involved filming the stop operations for a certain period, followed by processing and analyzing the video in a laboratory to extract the data required for both calibration and validation.

The calibrated parameters for the bus stop were the clearance time (t_c), dead time (β_0), boarding time (β_b), and alighting time (β_a). Following the calibration, a two-level validation process was conducted.

The first level involved comparing the average outputs obtained from the model with the field observations to assess the overall predictive power of the model. The outputs considered were the average steady-state statistics for various variables, including the capacity of the bus stop, degree of saturation, mean delay to buses for passengers transfer, in queue and total, and mean queue length. The outputs from the model and the actual system showed an overall similarity, with differences averaging within 10%.

The second level of validation involved a statistical comparison of the outputs. The method used was a confidence interval and hypothesis test for the mean based on the t distribution. The null hypothesis was that the mean values of the various outputs provided by the model and the actual system are not different with a given level of confidence. For all measured parameters, including waiting time, waiting pass, queue delay, passenger delay, and total delay, the test failed to reject the null hypothesis, indicating that the outputs from both the model and the actual system were not different.

In conclusion, all statistical tests performed provided evidence to support the resemblance of the model outputs with reality with a high level of confidence.

3.3.3 Application and results

A simulation was carried out to investigate the performance of a bus stop that received three types of buses, based on the number of berths it had. The results of the simulation were analyzed and compared to assess the effectiveness of the stop [10].

It was found that a one-berth stop could accommodate a flow of 47 buses per hour and a demand of 196 passengers per hour. However, queues developed upstream of the stop area, with up to three buses waiting in line and the third bus experiencing an 80-second wait. Additionally, 47% of the time, at least one bus was waiting in the queue.

Opening a second berth significantly improved the performance of the stop. The degree of saturation dropped from 42% to 22%, and the likelihood of queues developing was almost negligible. Based on the results of the simulation, it was concluded that a two-berth stop would be required.

In summary, the simulation model provided valuable insights into the performance of the bus stop, demonstrating the necessity of having two berths to improve the stop's overall efficiency.

3.4 Modeling and simulation

This thesis aims to develop a novel tool capable of modeling and simulating a tramway network. Therefore, an extensive review of relevant literature is imperative to enhance the understanding of the process of modeling and simulation. This section is dedicated to presenting the findings of the literature research. In [11], the author provides an excellent introduction on the development of simulations, and the following is a concise summary of the key points discussed.

3.4.1 What is modeling and simulation?

Modeling involves constructing a representation of a system of interest, such as a tramway network, while ensuring that the model is both similar to reality and simpler than the actual system. The primary purpose of a model is to enable analysts to predict the effects of changes on the system. A well-designed model strikes a balance between realism and simplicity, as the author aptly states, "A good model is a judicious tradeoff between realism and simplicity."

An important aspect of modeling is ensuring the validity of the model. Model validation techniques typically involve simulating the model using known input conditions and comparing the model's output with the actual system's output. By validating the model, its accuracy and reliability can be assessed.

Mathematical models used in simulations can be classified into different categories based on their characteristics:

- Deterministic models: These models have fixed input and output variables, without any element of randomness.
- Stochastic models: In contrast, stochastic models incorporate at least one probabilistic input or output variable, allowing for randomness and uncertainty.
- Static models: These models do not consider the element of time in their interactions.
- Dynamic models: Dynamic models take into account time-varying interactions among variables, capturing the temporal aspects of the system.

Considering the scope of this thesis, it is appropriate to develop a simulation that combines both stochastic and dynamic elements to accurately represent the tramway network and its behavior.

A simulation of a system involves operating a model that represents the system. This model can be reconfigured and experimented with, providing a cost-effective and practical alternative to making changes directly in the actual system. For instance, in real-life scenarios, it would be impractical and nonsensical to convert random single stops into double stops, analyze the outcomes, and then revert the changes. However, such experimentation is viable and valuable within a simulation environment. Simulations serve as tools to assess the performance of a system under various configurations of interest.

Simulations are employed prior to modifying an existing system or constructing a new one, aiming to minimize the risk of failure, identify potential bottlenecks, optimize resource utilization, and enhance overall system performance. Hence, conducting simulations before implementing changes to a tramway network, or even during its initial design phase, is of great significance.

The focus of this tutorial centers around discrete event simulation, which assumes that the system undergoes instantaneous changes in response to specific discrete events. While discrete event simulation may not capture the same level of detail as continuous simulation, it is simpler to implement and finds extensive application in various simulation scenarios.

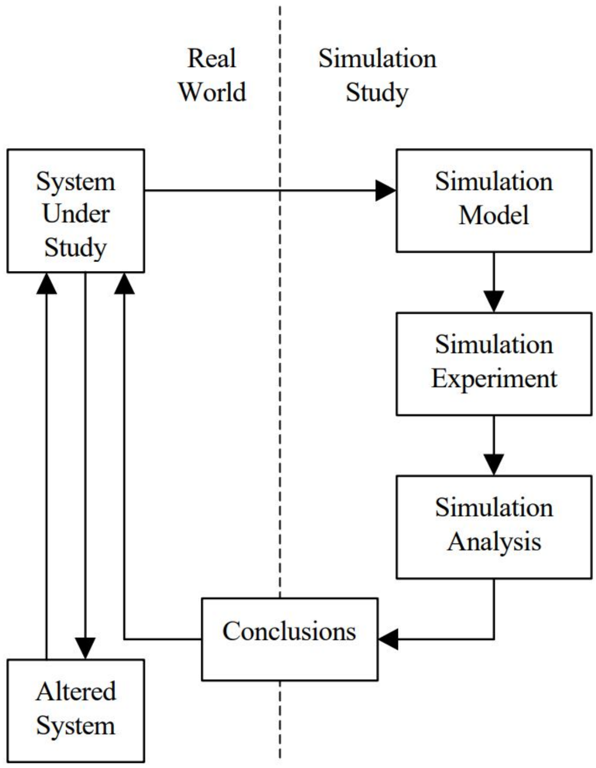

Fig. 3.5: Simulation Study Schematic [11]

Figure 1 illustrates a schematic outlining the process of conducting a simulation study. It is noteworthy that the only stage in which human intervention is not required is the actual execution of simulations, which is efficiently handled by most simulation software packages. However, it is crucial to emphasize that the presence of powerful simulation software alone does not guarantee the success of a simulation study. The author rightly points out that experienced problem formulators, simulation modelers, and analysts are indispensable for accomplishing a successful simulation study [11].

3.4.2 How to develop a simulation model?

Simulation models comprise several essential components, including system entities, input variables, performance measures, and functional relationships. The modeling phase is widely recognized as the most critical aspect of a simulation study, as the quality of the simulation model directly impacts the study's outcomes. The process of simulation modeling typically encompasses the following steps:

- Step 1. Problem Identification. Identify and enumerate the issues associated with the existing system. Establish the requirements for a proposed system.
- Step 2. Problem Formulation. Define the boundaries of the system or a specific part to be studied. Clearly articulate the overall objective of the study and identify specific issues to be addressed. Define performance measures as quantitative criteria for comparing and ranking different system configurations. At this stage, briefly outline the configurations of interest and formulate hypotheses regarding system performance. Determine the time frame for the study, such as a one-time decision or regular ongoing analysis. Identify the intended end user of the simulation model, whether it be corporate management or a production supervisor. It is crucial to formulate problems as precisely as possible.
- Step 3. Data Collection and Processing. Collect relevant data on system specifications, input variables, and performance of the existing system. Identify sources of randomness in the system, i.e., stochastic input variables. Select appropriate probability distributions for each stochastic input variable and estimate the corresponding parameters.
- Step 4. Model Formulation and Development. Develop schematics and network diagrams of the system. Translate these conceptual models into a form acceptable to simulation software. Verify that the simulation model executes as intended through various techniques, such as tracing, varying input parameters within acceptable ranges and comparing output, substituting constants for random variables and manually verifying results, and employing animation.
- Step 5. Model Validation. Compare the performance of the model under known conditions with the performance of the real system. Conduct statistical inference tests and seek input from system experts to validate the model. Assess the level of confidence that the end user places in the model and address any identified issues. For significant simulation studies, experienced consultants often recommend a structured presentation of the model by simulation analysts before an audience comprising management and system experts. This process ensures that the model's assumptions are correct, complete, and consistent, while also enhancing confidence in the model.
- Step 6. Documentation of the Model for Future Use.

3.4.3 How to design a simulation experiment?

A simulation experiment involves conducting tests in which meaningful changes are made to the input variables of a simulation model. This allows for the observation and identification of factors influencing changes in performance measures. The design of a simulation experiment revolves around determining the necessary data, its format, and quantity. The following steps outline the process of designing a simulation experiment:

- Step 7. Selection of Appropriate Experimental Design. Choose a performance measure and identify a few key input variables that are likely to influence it. Determine the levels or values for each input variable.

- Step 8. Establishment of Experimental Conditions for Runs. Consider the methods for obtaining accurate and informative data from each run. Assess whether the system under study is stationary (performance measure remains constant over time) or non-stationary (performance measure changes over time). In stationary systems, the focus is often on the steady-state behavior of the response variable. Determine whether terminating or nonterminating simulation runs are appropriate for the study. Select the run length, which defines the duration of each simulation run. Determine the appropriate starting conditions, such as starting the simulation with an empty and idle system or with a predefined number of customers in a queue at time 0. If necessary, specify the length of the warm-up period, which allows the system to reach a stable state before data collection begins. Decide on the number of independent runs, each utilizing a different random number stream while maintaining the same starting conditions. This consideration ensures an adequate sample size for the output data.

- Step 9. Execution of Simulation Runs.Perform simulation runs based on the design and conditions established in Steps 7 and 8 above.

3.4.4 How to perform a simulation analyses?

Most simulation packages offer run statistics, such as the mean, standard deviation, minimum value, and maximum value, for performance measures like wait time and inventory on hand. However, interpreting simulation results can be challenging, despite the absence of data collection errors, complete knowledge of the underlying model, and user-controlled replications and configurations. An observed outcome could be attributed to inherent system characteristics or merely a random event. While statistical inference techniques are typically employed to assess the significance of observed phenomena, many of these techniques assume independent and identically distributed data. Unfortunately, most simulation data exhibits autocorrelation, which violates this assumption.

The analysis of simulation output data involves the following steps:

- Step 10. Interpret and Present Results. Compute numerical estimates, such as the mean and confidence intervals, for the desired performance measures corresponding to each configuration of interest. When dealing with autocorrelated data, the batch means technique can be employed to obtain confidence intervals for the mean. In this approach, the original contiguous data set is replaced with a smaller data set consisting of means calculated from contiguous batches of the original observations. It is important to note that the assumption of independence among batch means may not always hold true. Increasing the total sample size and lengthening the batch size can help alleviate this issue. Additionally, test hypotheses regarding system performance and construct graphical displays, such as pie charts or histograms, to visualize the output data. Finally, document the obtained results and draw appropriate conclusions.

- Step 11. Recommend Further Course of Action. Based on the findings, recommend additional steps to be taken. This may involve conducting further experiments to enhance the precision and reduce bias in estimators, performing sensitivity analyses, or exploring alternative scenarios.

3.4.5 What makes a problem suitable for a simulation modeling and analyses?

In general, simulation serves as the preferred methodology for modeling and analyzing randomness within a system. Particularly, simulation modeling and analysis are employed in the following scenarios:

- Instances where certain processes within the real world cannot be observed either due to their impossibility or prohibitively high cost.
- Problems that can be formulated using mathematical models, yet lack analytic solutions either due to their impossibility or excessive complexity.
- Situations in which the validation of the mathematical model describing the system is unattainable or excessively expensive, often due to inadequate data availability.

3.5 Conclusions

In conclusion, this literature review has highlighted the main characteristics and insights discussed earlier and their relevance to the purpose of this thesis. The primary agents of a public transport stop have been identified, followed by a listing of the most significant features to consider when designing stops, such as type, micro and macro location, and the relevant categories within those features.

Moreover, a summary has been provided of how steady state formulas can be used to explain public transport models. While these formulas may lack precision, particularly when dealing with complex models, they serve as a valuable tool for a broader perspective and can inspire the development of more complex simulation models. Simulation models can be used when steady state formulas are insufficient. However, they require more time, development, and computational power to be executed, but they are more adaptable and can accurately reflect the reality.

A prime example of a simulation model is PASSION, which focuses on bus stops. The model has been explained in detail and will be a valuable guide for the development of new simulation models. Its results are consistent with reality and have passed rigorous statistical tests. Additionally, it demonstrates its ability to provide valuable knowledge that can be used to improve existing bus stops.

However, the review has revealed that PASSION is only capable of simulating one stop at a time, which leaves no room to explore the interaction between stops and the public transport network as a whole. It is a fascinating field that requires further investigation in the context of a connected public transport network. Can changes in one stop affect the performance of other stops positively or negatively? This area is worth exploring further in the development of this thesis.

As we approach the conclusion, a comprehensive examination has been conducted on the concepts of simulation and modeling, as well as the sequential steps required to construct a rigorous simulation experiment, encompassing data collection to the analysis of simulation results. This detailed exploration serves as a valuable and all-encompassing guideline, offering broad yet well-defined instructions.

Overall, this literature review has provided valuable insights into the field of public transport stop design and simulation modeling. The context that frames this field of study is now better defined.

Chapter 4

Modeling the simulation

The primary objective of this research is to investigate the capacity impact of double stops in a tramway network and quantify this impact under specific circumstances related to each stop. To accomplish this, a robust methodology has been devised, incorporating established theoretical foundations and innovative techniques.

The selection of an appropriate research design is crucial for the success of any empirical study. In this thesis, a simulation research design has been chosen based on the nature of the research questions and the availability of relevant data.

It is important to note that this thesis aims to develop a robust simulation tool capable of revealing insightful findings about tramway networks. However, the approach taken is general, intended to be applicable to various tramway networks. Real data is utilized to test the performance of the simulation. Thus, throughout the description of the simulation steps, there will be two parallel lines of explanation. The first line outlines the development of the general approach, while the second line describes how it is implemented in a specific real case. The Vienna Tramway Network has been chosen as the test data for this purpose.

4.1 Problem Identification

In tramway networks where different lines share the same stop, a significant challenge arises due to the risk of multiple vehicles arriving simultaneously. The existing infrastructure of single stops is not designed to efficiently handle the alighting and boarding of passengers to more than one vehicle at the same time. As a result, the last arriving vehicle is forced to wait until the preceding vehicle or vehicles complete their passenger exchange process. This waiting moment, although seemingly trivial, poses several detrimental effects on the overall health of public mobility. In this section, we will outline the reasons why this situation is problematic and needs to be addressed urgently.

Firstly, the issue of multiple vehicles waiting at a single stop leads to increased congestion and delays within the tramway network. As the last vehicle is compelled to wait for its turn, it not only disrupts the regular schedule but also impacts the punctuality of subsequent trips. This delay cascades through the entire network, potentially causing inconvenience to a significant number of passengers relying on efficient and timely tramway services.

Secondly, the waiting time resulting from the simultaneous arrival of multiple vehicles contributes to decreased passenger satisfaction and comfort. The passengers, expecting a smooth and seamless travel experience, are often confronted with crowded platforms and congested vehicles when they encounter this issue. The inconvenience caused by extended waiting times and overcrowding can lead to dissatisfaction, frustration, and even potential passenger safety concerns [12].

Furthermore, the inefficiency in handling simultaneous arrivals also affects the operational efficiency of tramway services. The waiting period for the last vehicle not only wastes valuable resources but also diminishes the overall system capacity. With limited time and resources, the transit authorities are unable to maximize the potential of their tramway networks, resulting in decreased productivity and suboptimal utilization of available assets.

The widely recognized solution to address this problem is the implementation of double stops. As mentioned in the literature review, double stops enable simultaneous passenger operations of two vehicles by expanding the stopping area to accommodate two berths. Typically, berths are arranged sequentially, resulting in a sequential double stop. However, parallel double stops, where berths are arranged side by side, are less common due to the additional width required in the pavement space, which often makes their implementation unfeasible.

However, there is a dearth of literature, at least up to the point of this thesis, regarding the quantitative improvement that the implementation of a double stop would bring. While it is acknowledged that double stops inherently enhance the capacity of a stop, the extent of this improvement remains unknown. Furthermore, the impact of double stops on the rest of the network is also uncertain. Will the implementation of double stops have ripple effects throughout the network? These questions warrant further investigation and analysis.

4.2 Problem Formulation

First and foremost, an accurate description of the problem is essential. The context involves an existing or proposed tramway network that consists of multiple lines. Crucially, these lines must intersect and share at least one stop along their respective routes. This condition is vital to ensure that the implementation of double stops can result in an actual increase in capacity. Without such intersections, the introduction of double stops would not yield any capacity improvements.

Most tramway vehicles travel in both directions in parallel situated tracks. However, it is worth noting that the zones where vehicles traveling in different directions operate are separate from each other. Consequently, there are no interference between vehicles traveling in opposite directions. Therefore, for the purposes of analysis, it is sufficient to consider only one direction for each tramway line.

In order to streamline the simulation process and focus on relevant aspects, certain simplifications can be implemented. A comprehensive replication of the entire tramway network is not necessary. Stops that are serviced by only one tram line hold no significance for the study and can be disregarded. Thus, it is more advantageous to exclude zones from the system that do not possess potential for improvements.

The simulation will be conducted within a predetermined time frame, preferably during peak hours of a typical working day when the frequency of vehicles is at its highest. By sizing the simulation based on the most challenging scenario, we can ensure that the tramway system functions smoothly throughout the remainder of the day. Consequently, the time frame is established, and the factors that influence the simulation will be derived from this specific period.

The following factors, influencing the performance of the tramway network, will be taken into account during the simulation:

- Tramway average speed: This parameter excludes the time when the tram is stationary, either due to traffic lights or when it is stationed at a stop.
- Distances between stops: The spatial intervals separating each consecutive stop are a critical determinant of the tram's overall travel time.
- Vehicle frequency of each line: This factor quantifies the rate at which vehicles join the tramway network, providing insights into the flow and demand on different lines.
- Traffic lights between stops: The presence of traffic lights along the route affects the speed and flow of the tram, potentially causing delays.
- The traffic light immediately following a stop: The behavior and configuration of this particular traffic light will be approached differently due to its unique location, requiring separate analysis.
- The type of stop: Stops can be categorized as single or double, where the latter refers to a sequential arrangement of two stops. For the purposes of this study, all double stops will be considered sequential.
- Passenger alighting and boarding time: The duration passengers take to disembark and board the tram significantly impacts the overall efficiency of the system.

The primary measure of interest to be tracked throughout the simulation is the Waiting Time at each stop. This metric is defined as the duration in which a vehicle intends to perform passenger operations but is unable to do so due to another vehicle obstructing the berth or berths. It is important to emphasize that time spent waiting at a stop due to a red traffic light is not considered as Waiting Time. The Waiting Time represents only a fraction of the total time a vehicle spends at a stop but is particularly significant as it can be reduced through the implementation of double stops.

4.3 Data Collection and Processing

This section aims to provide a more comprehensive explanation of the data that will serve as input in the simulation. Specifically, it will outline the methodology employed for the Vienna tramway network case and elaborate on the proper storage requirements for the data prior to its integration into the simulation.

The simulation model relies on two distinct types of data for its execution. The first type encompasses the data that defines the tramway network and serves as a prerequisite input for running the simulation. This data is essential as it provides the necessary information about the structure and characteristics of the specific tramway network under consideration.

The second type of data comprises predefined parameters that also influence the simulation results. These parameters, although generally applicable to all tramway networks, are not required to be introduced during every simulation run. They are considered universal defaults that ensure consistency and efficiency. However, it is important to note that these parameters can be modified by the simulation user if they deem it more appropriate to do so.

4.3.1 Input data

A standardized protocol has been established for storing the input data, utilizing a .txt file format with the following structure:
T
Va
m
$Sid_{0,1}; Sid_{0,2}; ...; Sid_{0,n}$
$Sd_{0,1}; Sd_{0,2}; ...; Sd_{0,n}$
$Stl_{0,1}; Stl_{0,2}; ...; Stl_{0,n}$
$St_{0,1}; St_{0,2}; ...; St_{0,n}$
Lf_0 $Sid_{1,1}; Sid_{1,2}; ...; Sid_{1,n}$
$Sd_{1,1}; Sd_{1,2}; ...; Sd_{1,n}$
$Stl_{1,1}; Stl_{1,2}; ...; Stl_{1,n}$
$St_{1,1}; St_{1,2}; ...; St_{1,n}$
Lf_1
.
.
.
$Sid_{m,1}; Sid_{m,2}; ...; Sid_{m,n}$
$Sd_{m,1}; Sd_{m,2}; ...; Sd_{m,n}$
$Stl_{m,1}; Stl_{m,2}; ...; Stl_{m,n}$
$St_{m,1}; St_{m,2}; ...; St_{m,n}$
Lf_m

Now, an explanation will be provided for each parameter used in the file:

- T. Simulation Time. This refers to the real-time duration, measured in seconds, for which the simulation will be executed.
- Va. Average Velocity. he average velocity is calculated for the entire tramway network, considering that in a highly interconnected subset of lines, the vehicle velocities tend to be similar. It should be noted that this value does not account for any stops; it solely represents the velocity of the vehicle while in motion, as the consideration of stops will be addressed in a separate section.
- m. Number of lines. This denotes the total count of lines comprising the tramway network, or at least the specific subset under investigation.
- n. Number of stops on a certain line. This indicates the quantity of stops present on a given line. It is important to highlight that the number of stops may vary across different lines, as each line may have a distinct number of stops.
- $Sid_{i,j}$. Stop Identification Number. The stop identification refers to a unique numerical identifier assigned to each stop within the system. This identifier serves the purpose of both distinguishing individual stops and alleviating the need to use the complete and potentially lengthy names of the stops. The subscripts are utilized to denote the line to which the stop

corresponds, where $i = 1 \ldots m$, and the stop's position on the line, where $j = 1 \ldots n$. The first stop in each line is considered the entry stop and the last one the exit stop, meaning that in the first one the vehicle arrive, then go through the rest of stops according to the path and, at the end, leaves the line in the last stop.

- $Sd_{i,j}$. Distance to the next stop. This signifies the distance, measured in kilometers, between the current stop (identified by the subscripts) and the subsequent stop. Similarly, the subscripts indicate the line to which the distance refers, where i = 1 ... m, and the position of the stop on the line, where j = 1 ... n.
- $Stl_{i,j}$. Number of traffic lights. This value represents the total count of traffic lights encountered by the tramway when approaching the next stop. The subscripts denote the line and the stop position on that line, where i = 1 ... m, and j = 1 ... n, respectively.
- $St_{i,j}$. Stop type. This is a binary variable that assumes the value 0 if the stop is a single stop and 1 if the stop is a double stop. Again, the subscripts denote the line and the stop position on that line, where i = 1 ... m, and j = 1 ... n, respectively.
- Lf_j. Line Frequency.This denotes the time interval, measured in seconds, between the arrivals of vehicles at the initial stop of a line. As different lines may have varying frequencies, the flexibility to assign distinct frequencies to each line is provided. However, if all lines operate with the same frequency, a single value can be used for all lines. In this case, the subscript i indicates the line to which the frequency pertains, where i = 1 ... m.

4.3.2 Vienna Tramway Network Data

The Vienna Tramway Network, as of 2019 [13], comprises a comprehensive transportation system consisting of 28 tram lines. These lines are supported by four tram depots, excluding satellite tram stations, that facilitate the operational needs of the network. A remarkable feature of the network is its extensive coverage, encompassing a total of 1,076 stops strategically located throughout the city. All the following Vienna Tramway Network stats has been extracted from [13].

To ensure efficient passenger flow, the average distance between stops is measured at 396 meters. This arrangement allows for convenient access to tram services, promoting seamless travel experiences. The average line length of the Vienna Tramway Network spans approximately 8.1 kilometers, accommodating both short-distance and longer commutes within the city.

The Vienna Tramway Network boasts an impressive network length of 175.6 kilometers, with the operational network spanning 172 kilometers. The total length of the lines encompasses 225.4 kilometers, constituting an extensive infrastructure that supports the efficient operation of the tramway system. The track length totals 420.6 kilometers.

To cater to passenger demand, an average of 398 trains are in operation from Monday to Friday. The network possesses a fleet of 478 tramcars, including 140 articulated tramcars and 338 ultra-low-floor articulated trams (ULF, Flexity). In addition, 134 trailers are available to accommodate passenger volume and enhance the network's capacity. The tramcars collectively offer 85,806 seats, and the average vehicle capacity stands at 140.2 passengers.

Notably, the Vienna Tramway Network is a crucial mode of transportation for the city, serving a substantial number of passengers. In 2019, the network recorded 304.8 million passengers, highlighting its significance as a reliable and widely utilized public transport option.

The network incorporates dedicated tram routes separated from private traffic, accounting for 53.6% of the total network. This separation contributes to improved efficiency and reliability in tram operations. Furthermore, the network features 220 caps, which are extended footpaths that enhance pedestrian safety and accessibility near tram stops.

However, as previously mentioned, it is not necessary to simulate the entire tramway network, as many stops have only one assigned line and do not hold relevance for the scope of this thesis. Therefore, the focus of the simulation will be on a specific subset of stops, namely those encompassing the Vienna Ring. This selection is made due to the significance and importance of these stops within the context of the study.

The Vienna Ring, also known as the Ringstraße, is a prominent boulevard that encircles the historic city center of Vienna, Austria. It is a grand and iconic road that stretches for approximately 5.3 kilometers and forms a ring-like shape, hence its name. From an urbanistic perspective, the Vienna Ring holds significant importance in the city's urban fabric and public transport infrastructure. The creation of the boulevard was a visionary urban planning decision that transformed Vienna's city center and had a profound impact on its development.

As a major transportation route, the Vienna Ring provides efficient access and circulation for both private vehicles and public transport. The boulevard accommodates a significant amount of traffic, including buses, trams, and taxis, serving as a vital artery for moving people in and out of the city center. The efficient integration of public transport along the Vienna Ring ensures convenient mobility for residents and visitors, reducing dependency on private vehicles and promoting sustainable transportation options. In the figure 4.1 a map of the Vienna Ring can bee seen, including its tram stops.

Figure 4.2 represents an elaborated depiction of the tramway network encompassing the Vienna Ring at the moment of writing (2023), which encompasses 14 distinct stops served by 5 tram lines. It is important to note, however, that the simulation will employ identification numbers instead of the actual names of the stops and lines. Tables 4.1 and 4.2 provide the correspondence between the identification numbers and the respective names of the lines and stops for clarity and reference.

To conclude this section, it is imperative to explain the methodology employed for collecting the data required to construct the aforementioned .txt file. Initially, the timetables for the tram lines constituting the Vienna Ring Tram Network were scrutinized using time-tables from [16]. It was observed that the peak hours for all lines span from 7 am to 10 am, during which the frequency of vehicles passing through the entry stop is highest. Consequently, two key pieces of information were extracted: a simulation duration of 3 hours, equivalent to 10,800 seconds, and the frequencies for each line, which amounted to a vehicle every 6 minutes (360 s) for lines D, 1, 2, and 71, and every 6 minutes and 40 seconds (400 s) for line U2Z.

It should be noted that a simplification has been made in this analysis, as the frequencies in question are not constant for the entire three-hour simulation across all lines. The situation varies depending on the specific line and stop. However, observations indicate that certain lines exhibit a different frequency between 7 and 9 a.m., and perhaps a lower frequency between 9 and 10 a.m. Nevertheless, this pattern is not applicable to all lines. Therefore, for the purpose of simulating the worst-case scenario, it has been assumed that the line frequency considered is the

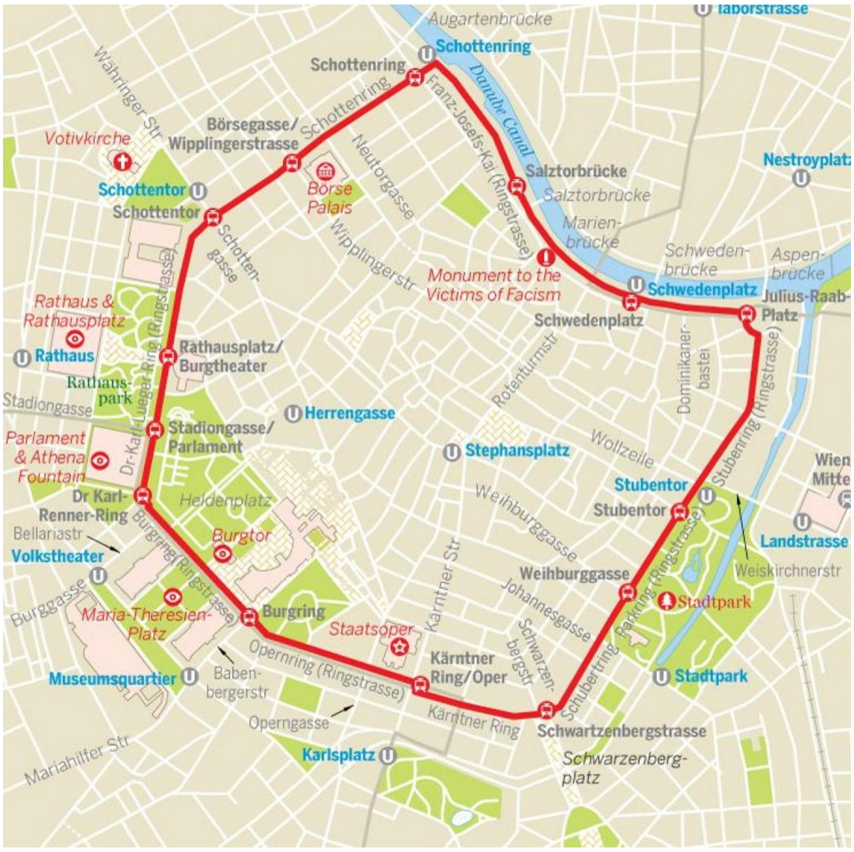

Fig. 4.1: Vienna Ring Map with tram stops from [14]

Stop Name	ID
Schottenring	1
Börse	2
Schottentor	3
Rathauspl., Burgtheater	4
Parlament	5
Ring, Volkstheater	6
Burgring	7
Oper, Karlsplatz	8
Schwarzenbergpl.	9
Weihburgg.	10
Stubentor	11
Julius-Raab-Pl.	12
Schwedenpl.	13
Salztorbr.	14

Tab. 4.1: Vienna Ring Tramway Stops IDs

Line Name	ID
D	0
1	1
2	2
71	3
U2Z	4

Tab. 4.2: Vienna Ring Tramway Line IDs

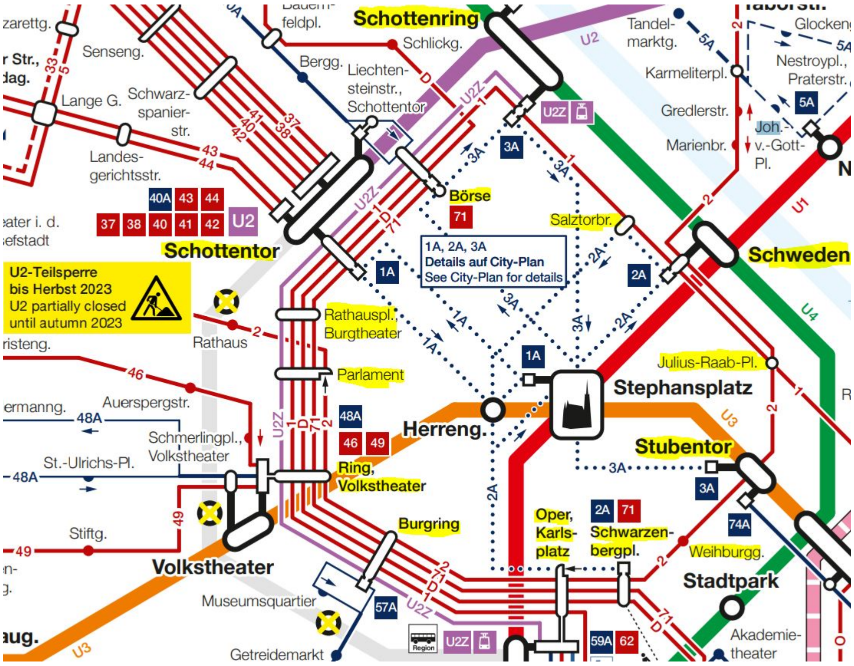

Fig. 4.2: Vienna Ring Map Tramway Network Detailed from [15]

highest frequency observed during the three-hour window.

According to information obtained from [17], the majority of tram vehicles maintain an average speed ranging between 20 and 30 km/h. However, estimating an accurate value becomes challenging due to the inherent variability arising from factors such as acceleration and deceleration during travel, even after accounting for the time spent at each stop. Consequently, for the purposes of this study, selecting an average speed of 25 km/h appears suitable. It is essential to emphasize that the velocity mentioned refers to the average speed at which the tramway vehicle operates while in motion. The commercial speed, on the other hand, takes into account the duration of stops at traffic lights and designated stops, resulting in a lower average speed compared to the "in-motion" speed. The commercial speed considers the overall travel time, including periods of halted movement, and provides a more comprehensive understanding of the tram's operational efficiency.

Lastly, with the number of lines and stops already determined from the previously presented maps, the remaining data consists of the distances between stops, the number of traffic lights encountered between stops, and the categorization of stops. Distances and information regarding traffic lights were acquired from [18], an interactive map that facilitated the overlaying and removal of information layers, alongside a measuring tool for precise measurements. On the other hand, the classification of stops as single or double was manually verified using Google Maps and corroborated by Wiener Linien. In this manner, a .txt file similar to the following was obtained:

Txt file Sample:
10800
25
5
2; 3; 4; 5; 6; 7; 8; 9
0, 388; 0, 358; 0, 42; 0, 403; 0, 441; 0, 361; 0, 424; 0, 372
3; 3; 3; 3; 2; 1; 2; 2
1; 1; 1; 1; 1; 1; 1; 1
360
12; 13; 14; 1; 2; 3; 4; 5; 6; 7; 8
0, 449; 0, 379; 0, 421; 0, 39; 0, 388; 0, 358; 0, 42; 0, 403; 0, 441; 0, 361; 0, 424
2; 1; 1; 2; 3; 3; 3; 3; 2; 1; 2
0; 0; 0; 1; 1; 1; 1; 1; 1; 1; 1
360
5; 6; 7; 8; 9; 10; 11; 12; 13
0, 403; 0, 441; 0, 361; 0, 424; 0, 372; 0, 403; 0, 447; 0, 449; 0, 379
3; 2; 1; 2; 2; 1; 3; 2; 1
1; 1; 1; 1; 0; 1; 1; 0; 0
360
2; 3; 4; 5; 6; 7; 8; 9
0, 388; 0, 358; 0, 42; 0, 403; 0, 441; 0, 361; 0, 424; 0, 372
3; 3; 3; 3; 2; 1; 2; 2
1; 1; 1; 1; 1; 1; 1; 1
360
1; 2; 3; 4; 5; 6; 7; 8
0, 39; 0, 388; 0, 358; 0, 42; 0, 403; 0, 441; 0, 361; 0, 424
2; 3; 3; 3; 3; 2; 1; 2
1; 1; 1; 1; 1; 1; 1; 1
400

4.3.3 Predefined Parameters

There are two fundamental concepts that have been universally defined in the simulation, irrespective of the input data. These concepts are dwell time, which represents the time taken to perform alighting and boarding operations for passengers, and the time spent at traffic lights between stops. In this context, a simplified approach has been adopted for both aspects. However, extensive literature exists that presents complex models incorporating numerous parameters. For instance, the Social Force Model [19] has been used to study dwell time.The Social Force Model is a computational framework widely employed in the field of pedestrian dynamics and crowd simulation. It aims to simulate the movement and interactions of pedestrians in crowded environments, capturing emergent behavior and collective dynamics resulting from individual interactions and social forces that influence pedestrian movement. In this model, pedestrians are considered as individual agents, and their movements over time are simulated by incorporating equations that calculate the net forces acting on them based on factors like position, velocity, and environmental and interpersonal forces. By iteratively updating these forces and simulating system dynamics, the model can predict collective crowd behavior, including flow patterns observed in tram stations.

The choice of employing a simpler model, such as a normal distribution, to represent dwell time in the simulation is driven by the understanding that passenger behavior is influenced by a multitude of factors beyond the scope of this thesis. Factors such as individual preferences, passenger characteristics, and situational context can significantly impact dwell time. Consequently, attempting to capture the intricacies of passenger behavior through a complex model like the Social Force Model may lead to overfitting or an unrealistic representation of real-world scenarios. By utilizing a normal distribution with parameters extracted from [20], the simulation aims to provide a reasonable approximation of dwell time while maintaining computational efficiency.

This article [20] delves into the significance of dwell time in accurately determining the arrival time and scheduling of public transportation systems, with a specific focus on Tramway dwell time. While previous studies have explored dwell time for buses and light rail transit, there is a dearth of research specifically addressing Tramway dwell time. To address this gap, the present study aims to model Tramway dwell time through multiple linear regression analysis, utilizing data collected from the Kabataş Bağcılar tramway in Istanbul, Turkey.

However, since many of the variables employed in this study to explain dwell time are not available for the Vienna Ring and tramway networks in general, the linear regression model cannot be utilized. Instead, the dwell time measurements during peak hours on weekdays will be used to estimate a normal distribution that can effectively explain dwell time in the simulation. This will be accomplished by calculating the mean and standard deviation for the simulation.

Furthermore, in a similar manner, an average time loss of 8 seconds per traffic light has been assumed for each traffic light encountered in the simulation between stops (not right after). This estimation is derived from a detailed analysis of the traffic light cycle on Vienna Ring, a well-known road network. The precise details and methodology for determining this average time loss will be expounded upon in the subsequent section 4.4.4, providing a comprehensive explanation of the considerations and calculations involved.

Lastly, the traffic light cycle for the Vienna Ring was provided by individuals from Wiener Linien. Wiener Linien is the public transportation company responsible for operating the tramway, bus, and subway systems in Vienna, Austria. It manages the extensive public transportation network and plays a vital role in ensuring efficient and reliable mobility for residents and visitors. According to the information provided by Wiener Linien, the traffic lights on the Vienna Ring follow a fixed cycle. The cycle duration is 100 seconds, comprising approximately 60 seconds of green light and 40 seconds of red light. This cycle determines the timing and sequencing of the traffic lights along the Vienna Ring, a significant road network encircling the central part of Vienna.

4.4 Model Formulation and Development

After thorough research, it was determined that the most suitable approach for modeling the simulation was to implement it using the programming language *Python 3.10*. Python exhibits remarkable compatibility with simulation tasks owing to its user-friendly nature, adaptability, and comprehensive scientific computing capabilities. The language boasts a diverse array of libraries, including *NumPy*, *SciPy*, and Pandas, which offer robust resources for numerical computations, data analysis, and simulation modeling. These libraries facilitate the efficient handling of extensive datasets, intricate mathematical operations, and statistical analyses, thus establishing Python as a favored choice for simulations across a multitude of disciplines, ranging from physics and biology to economics and engineering.

Furthermore, Python's inherent simplicity and readability significantly expedite the development and debugging of simulation code. Its lucid syntax empowers researchers and scientists to concentrate on the logic and algorithms of the simulation, rather than becoming entangled in convoluted language intricacies. In essence, Python's extensive collection of scientific computing libraries, coupled with its straightforwardness and flexibility, position it ideally for simulation purposes. This comprehensive ecosystem enables researchers and scientists to adeptly implement and analyze simulations, facilitating the acquisition of valuable insights and the informed decision-making process based on the outcomes of the simulations.

4.4.1 General Approach

An definition of the general structure of the simulation will now be presented. However, prior to delving into the details, it is imperative to establish some fundamental concepts.

- Asynchronous simulation entails a simulation paradigm characterized by the occurrence of events at irregular or unpredictable intervals. Under this approach, events are not synchronized with a fixed time step or a global clock. Instead, events are scheduled based on their own internal logic or external factors. Within an asynchronous simulation, events may be processed out of sequence and exhibit variable durations. This inherent flexibility enables the modeling of systems where events unfold in a more realistic and dynamic manner.

- State variables encapsulate the attributes or characteristics of the simulated system. They encapsulate the current state of the system and are commonly employed to describe its properties or conditions at a given point in time. State variables may encompass pertinent information such as position, velocity, temperature, or any other data that signifies the system's state. Throughout the simulation, these variables are updated and modified as events occur, thereby influencing the system's state.

- The events list constitutes a data structure employed in simulation to maintain a record of forthcoming events that necessitate processing. It encompasses pertinent details regarding each event, including its scheduled time and the specific action or function to be executed when the event transpires. The events list is organized based on the scheduled times of events, with the next event to be processed occupying the foremost position. During simulation, events are retrieved from the events list in chronological order, and their corresponding actions are executed. Subsequent to event processing, additional events may be appended to the list if they are triggered by the current event or arise from the simulation's progression.

- The simulation clock symbolizes the passage of time within the simulation. It serves as a reference point for event scheduling and facilitates the measurement of simulation duration. In asynchronous simulations, the clock is frequently virtual and decoupled from real-time. Typically, it is an abstract representation employed to manage the temporal aspects of the simulation. The clock is incremented or updated as events are processed, enabling the simulation to advance in time. This temporal mechanism ensures that events are scheduled and executed at appropriate intervals within the simulation.

- A statistics counter constitutes a mechanism employed in simulation experiments to collect and monitor pertinent data or metrics throughout the simulation run. Its primary purpose is to observe and record the behavior, performance, or specific outcomes of the simulated system. The statistics counter can accumulate values, compute averages, track frequencies, or store any other statistically significant information based on the observed events and state variables during the simulation. The data collected by the statistics counter can be analyzed subsequent to the simulation to gain insights into the behavior or performance of the system.

Now that these concepts have been introduced, the following is a general explanation of the simulation.

The simulation encompasses two distinct types of state variables: queues at tram stops and the color of traffic lights. The number of vehicle queues within the tramway network corresponds to the total count of different stops. In each queue, the first vehicle is engaged in passenger operations. If there are additional vehicles in the queue, they patiently await the completion of boarding and alighting by the foremost vehicle. Once the first vehicle concludes its passenger operations, subsequent vehicles may commence their own passenger operations or advance one position in the queue. However, this scenario applies solely to single stops. In the case of double stops (sequential double stops are exclusively considered), the first two vehicles are capable of performing passenger operations simultaneously, while the remaining vehicles in the queue await their turn. Once the passenger operations are finalized, the vehicles are permitted to depart based on the traffic light status at the respective stop. This traffic light serves as the second type of state variable. Each stop is equipped with a traffic light that alternates between green and red based on a predetermined time cycle. If the light is red, vehicles are prohibited from leaving the station, regardless of their completion of passenger operations.

As the simulation progresses, the statistics counter undergoes continuous updates contingent upon the queue status at each stop. These statistics counters encompass various metrics, including the number of vehicles that have passed through a given stop, vehicles that have encountered waiting periods, the percentage of vehicles subjected to waiting, waiting time for each vehicle, total waiting time, and more. A subsequent section will provide comprehensive details on these statistics counters.

At the commencement of the simulation, the clock is initialized to 0, queues are empty, and statistics counters possess no values. However, an event list comprising a series of pre-defined events is prepared. Each event comprises four attributes:

- Clock: Represents the designated time when the event is scheduled to occur.
- Event Type: Specifies the nature of the event, such as vehicle arrival, departure, or traffic light transition. Further elaboration on event types will be presented subsequently.
- Line: Indicates the associated line to which the event pertains. It is important to note that certain cases may involve an empty attribute for this field.

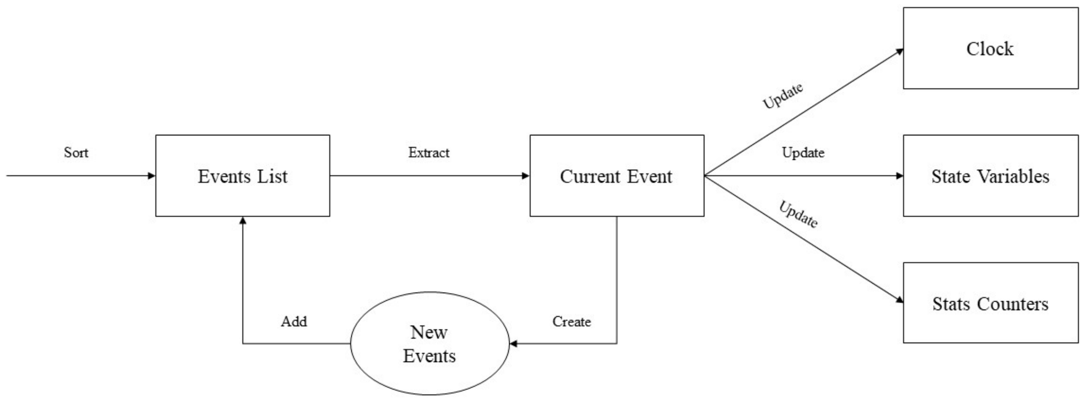

Fig. 4.3: Simulation Visual Representation

- Stop: Similar to the previous attribute, this identifies the relevant stop for the event. In this case, a stop assignment is always assigned to this attribute, in contrast to the line attribute.
- Position: Some events necessitate knowledge of the vehicle's position within a stop (relevant only to double stops), specifically whether it is the first or second vehicle.

A set of initial events is populated within the event list to establish the simulation's initial conditions. During each iteration of the simulation, the event list is sorted based on the event's clock, ensuring that the event with the earliest occurrence is processed first. Subsequently, the initial event from the sorted list is selected, the simulation clock is updated to match the event's clock, state variables are modified accordingly, statistics counters are adjusted, and new events may be appended to the event list. Prior to the subsequent iteration, the event list is once again sorted based on the event's clock.

This iterative process continues until the simulation clock reaches the specified maximum time, as defined by the input data, as previously explained. Figure 4.3 presents a visual representation illustrating the operational flow of a simulation iteration. Having provided the general explanation of the simulation, the following sections will delve into a more detailed explanation of each module within the simulation.

4.4.2 Input data processing - *get_data.py*

Before commencing the simulation, the input data needs to be processed using a specific program called *get_data.py*. The following provides a brief explanation of its functionality.

The code begins by opening a file specified by the *"path"* and *"file"* variables. It proceeds to read the first three lines of the file, which contain essential information regarding the simulation's duration, vehicle speed, and the number of lines.

Next, the program enters a loop based on the number of lines specified. During each iteration, it retrieves information concerning the stops along the line, distances between stops, traffic lights at junctions, stop types, and the line's frequency. This data is then stored in a dictionary structure named *"data_lines"*. By referencing the line and stop, one can access the desired attribute of that particular definition. For instance:

data_lines[2][7]['next'] = 8

This example signifies that, for line 2 and stop 7, the next stop is being inquired, which yields 8 as the result.

Lastly, another dictionary structure is created, incorporating the aforementioned *"data_lines"* dictionary under the key *"lines"*. Additionally, information such as the maximum simulation time, speed, and vehicle frequencies are stored in separate keys within the outermost dictionary. With the system fully defined and all necessary preparations completed, the simulation is now poised to be executed.

4.4.3 Initial Conditions - $initialize\_varialbes(data)$

In the forthcoming section, we will delve into the explanation of each type of event. However, it is pertinent to first introduce the initial conditions.

To initiate the simulation, a function named "$simulate(data)$" has been developed. It takes as input the dictionary output obtained from the previously discussed "$get\_data(path, file)$" function. The function establishes the initial conditions by setting the clock to 0 and defining the simulation end time, as specified in the input data (e.g., 10,800 seconds for the Vienna Ring scenario). Additionally, the duration for the traffic light cycles is defined, where, as previously mentioned, the green phase lasts for 60 seconds, followed by the red phase of 40 seconds.

Subsequently, a dictionary named "$stops_dat$a" is created to encompass the statistics counters that will serve as the output of the simulation upon its completion. This dictionary consists of a key for each stop (14 in the case of the Vienna Ring), with each stop associated with a total of 10 statistics counters. For now, we will only define four of these counters, which are as follows:

- '$n\_vehicles$'. Number of vehicles that have passed through the stop.
- '$n\_waited\_vehicles'$. Number of vehicles that have passed through the stop.
- '$waiting\_time$'. Total waiting time of vehicles at the stop.
- '$max\_waiting\_time$'. Maximum waited time for one vehicle at the stop.

At the beginning of the simulation, these four counters are initialized to 0. Furthermore, the same dictionary, "$stops\_data$", also stores the state variables for each stop, namely the queue of vehicles and the state of the traffic light immediately after the stop.

Following this, the events list is created, initially empty. However, it will soon be populated with the events that govern the behavior of the traffic lights.

Discussions were held with two colleagues from Wiener Linien, Dipl.Ing. Robert Dangl and Dipl.Ing. Stefan Edlinger, affirming that, for the scope of this thesis, it suffices to synchronize the switching of all traffic lights simultaneously. Nevertheless, the simulation is designed to accommodate individualized behavior for each traffic light. Consequently, at the simulation's onset, all traffic lights are set to green. After 60 seconds, 14 "TLR" (Traffic Light Red) events are triggered, one for each stop, causing all traffic lights to transition to the red state when the simulation clock reaches 60 seconds. Subsequently, 14 "TLG" (Traffic Light Green) events are scheduled to occur 40 seconds later (100 seconds from the simulation start), leading to the switch of all traffic lights back to green. This pattern continues until the end of the simulation (10,800 seconds). Therefore, if we examine the events list for stop 9 after the initial conditions are established, it would resemble the following:

events_list = [[60, 'TLR', None, 9], [100, 'TLG', None, 9], [160, 'TLR', None, 9], [200, 'TLG', None, 9], [260, 'TLR', None, 9], ..., [10,760, 'TLR', None, 9], [10,800, 'TLG', None, 9]]

It should be noted that the third attribute of each event is "$None$" for all events. This signifies that the third attribute represents the line to which the event pertains. However, since the traffic light switches are not specific to any particular line, this field is left empty. The example provided is a condensed representation, and in reality, there would be 13 additional events for each of the other stops. Consideration is being given, particularly for the Vienna Ring scenario, where all traffic lights are synchronized, to create a single event that triggers the simultaneous switching of all traffic lights. This approach would enhance efficiency as it would yield the same outcome with a single iteration of the main simulation loop, instead of 14.

Moving forward with the initial conditions, once the behavior of the traffic lights has been defined, it becomes necessary to establish the arrival of the first vehicles at the starting points of each line in the tramway network as specified in the input data.

To accomplish this, a vehicle arrival event is added to the event list at the first stop of each line, precisely at the beginning of the simulation (time 0). In the case of the Vienna Ring scenario, there will be a total of 5 vehicles (corresponding to the 5 lines of the Vienna Ring) arriving at the following stops: Schottenring, Börse (two vehicles), Parlament, and Julius-Raab-Pl. These stops are numbered as 1, 2, 5, and 12, respectively.

Following a similar pattern, for each line, a new vehicle arrival event is added to the first stop of the line every X seconds, where X denotes the frequency of that particular line. However, a slight modification has been implemented specifically for the Vienna Ring. Since both lines D and 71 share the same entry stop, it would be inequitable to have vehicles arrive at the exact same moment, which would significantly impact the waiting time due to queuing. Hence, an offset of half the frequency has been introduced for line D. Consequently, the two entry vehicles are not compelled to coincide each time there is an arrival.

After executing these sections of code, the event list, excluding the traffic light events, should resemble the following:

events_list = [[180, 'VA', 0, 2], [0, 'VA', 1, 2], [0, 'VA', 2, 5], [0, 'VA', 3, 2], [0, 'VA', 4, 1], [360, 'VA', 0, 2], [540, 'VA', 1, 2], [360, 'VA', 2, 5], [360, 'VA', 3, 12], [360, 'VA', 4, 1], ...]

This sequence continues until the end of the simulation time (10,800 seconds).

However, if we consider only these initial conditions for the simulation, it would imply that at time 0, all the stops in the tramway network are empty except for the entry stops. This approach is not realistic because, in reality, at time 0, each line is fully occupied with trams either stopped or approaching every X stops. Neglecting this aspect would require a warm-up time for the simulation to transition from a transitory state to a stationary state. Therefore, an additional 'VA' event has been incorporated into all the lines at every 4th stop at time 0 (except for line 1, that has them at time 180).

The purpose of the 'VA' event is to reflect the realistic occupancy pattern of each line. For instance, in the case of Line D on the Vienna Ring, which consists of stops from 12 to 8, at time 0, there will be three 'VA' events: one at stop 12, as previously explained because it is the entry stop, and two more at stops 2 and 6.

The decision to include a 'VA' event every 4 stops is based on the observation that most lines in the simulation exhibit a 6-minute (360 seconds) interval between vehicles entering the line, and the average travel time for a vehicle from one stop to the next is approximately 1.5 minutes (90 seconds). Consequently, when a vehicle is arriving at stop X0, stops X1, X2, and X3 should be unoccupied (for that particular line), while stop X4 should have a vehicle arriving at roughly the same time.

It is important to note that this adjustment needs to be manually customized for each simulated tramway network, as it is specific to the case of the Vienna Ring.

By following this approach, the initial and subsequent vehicle arrivals during the simulation are effectively defined and all the initial conditions are finished.

4.4.4 Simulation Main Loop - $simulate(data)$

Now that all the initial conditions have been established, the program will commence running events iteratively, one by one. Each event will bring about changes in the simulation's state variables and may also introduce new events to the events list. Therefore, we will now provide a comprehensive explanation of the various event types, their effects on the system, and the events that can be generated from other events.

For each type of event, there are two governing functions: the main function, which executes the event itself and modifies the system when an event of that type occurrs in the simulation, and the add event function, which is called by the main function from another event. For example, if a vehicle is ready to depart from a stop but encounters a red traffic light, and subsequently a 'TLG' event (Traffic Light Green) occurs at that stop, the 'TLG' event will likely add a 'VD' event (Vehicle Departure) to that stop. As a result, the vehicle will depart from the stop in the next iteration of the simulation.

'VA' Event - Vehicle Arrival:
This event signifies the arrival of a vehicle from a specific line at a particular stop at a defined time. 'VA' events are added to the events list in two ways: through the initial conditions and via the 'VD' event, under specific conditions that will be explained in the section dedicated to that event.

When a vehicle departs from a stop, except for the last stop on the line, it proceeds to the next stop. Therefore, the travel time is calculated to determine when the vehicle will arrive at the next stop, relative to the current time. This calculation is performed using the following equation 4.1:

$$Clock_{VA} = Clock_{VD} + t_{trip} \tag{4.1}$$

$Clock_{VA}$: clock at the moment the vehicle arrives to the next stop [s].
$Clock_{VD}$: clock at the moment the vehicle departs from the previous stops [s].
t_{trip}: trip time. Time it takes to the vehicle go from the departing stop to the arriving stop [s].

The trip time is derived from two components, as shown in Equation 4.2. The first component refers the distance between the current stop and the next stop, which is obtained from the input data. By employing Equation 4.3, the calculated travel time can be determined.

$$t_{trip} = t_{moving} + t_{stopped} \tag{4.2}$$

$$t_{moving} = \frac{dist_{i,j} * 3600}{v} \tag{4.3}$$

t_{moving}: trip time where the vehicle is in motion [s].
$dist_{i,j}$: distance between the departing, i, and the arriving, j, stop [km].
v: tramway speed, defined by the input of the simulation [km/h].

However, this time only accounts for the duration of the vehicle's movement. It is known that during tramway trips between stops, there can be delays caused by traffic lights and other traffic-related incidents. Therefore, the second part of the travel time considers the number of junctions with traffic lights and calculates the time spent stopped at these junctions using Equation 4.4.

$$t_{stopped} = juncs_{i,j} * 8 \tag{4.4}$$

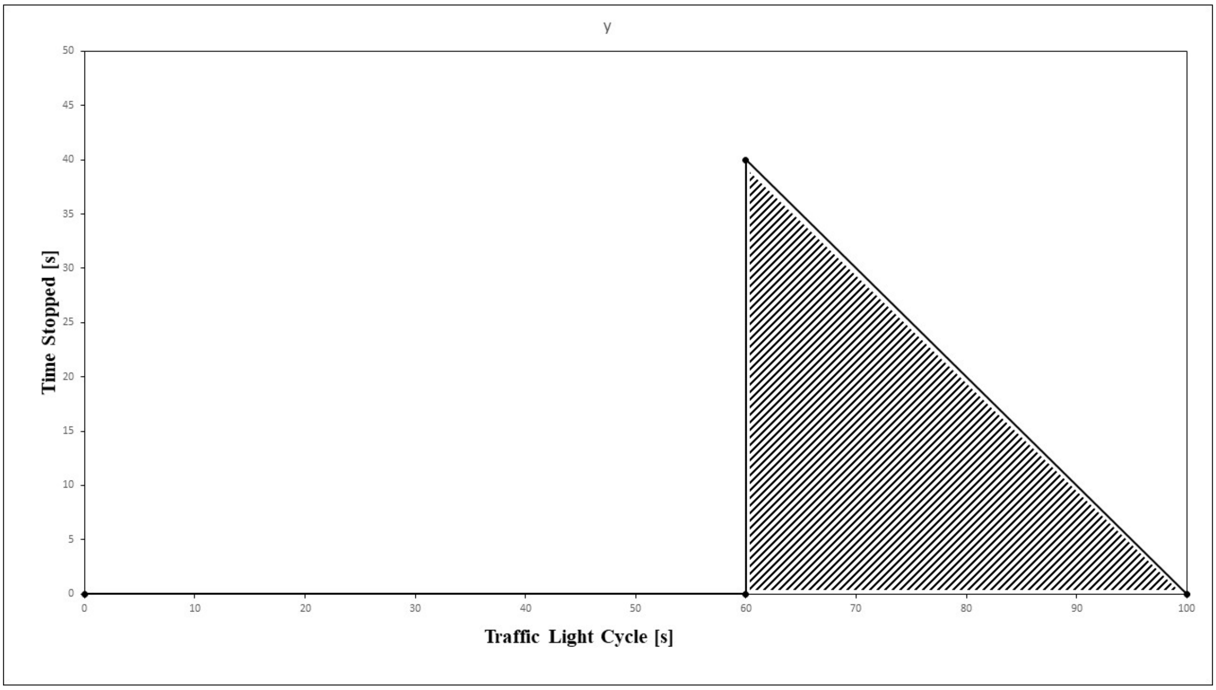

Fig. 4.4: Stopped time of a vehicle depending on the moment of the cycle when arrives

$t_{stopped}$: trip time where the vehicle is stopped at junctions [s].
$juncs_{i,j}$: number of junctions between the departing, i, and the arriving, j, stop.

Essentially, Equation 4.4 states that based on the number of junctions along the trip, the vehicle will spend an average of 8 seconds stopped at each junction. This value of 8 seconds is derived from the natural cycle of traffic lights on the Vienna Ring (though it can be calculated for a different cycle as well). Figure 4.4 illustrates the time a vehicle must wait at a junction depending on the phase of the traffic light cycle. Equation 4.5 mathematically represents Figure 4.4.

$$f(t) = \begin{cases} 0, \text{ if } t < 60 \\ 100 - t, \text{ if } t \geq 60 \end{cases} \tag{4.5}$$

During the first 60 seconds, the vehicle does not need to wait at all to pass through the traffic light, as it corresponds to a green traffic light. However, at the 60-second mark, when the light changes to red, the vehicle must wait for the remaining time until the end of the light cycle. For example, if the vehicle arrives at 60 seconds, it will wait for 40 seconds; if it arrives at 80 seconds, it will wait for 20 seconds, and if it arrives at the end of the cycle, it will not have to wait again as the light will turn green once more.

Given this information, the average time spent at a traffic light can be calculated as the average value of this function. The average value of the function can be determined by finding the integral between the two limits of the light cycle and dividing it by the duration of the cycle itself. In other words, the average time spend at a traffic light (t_{mean}) is equivalent to calculating the area under the function, which consists of a rectangle triangle, divided by the traffic light cycle, as depicted in Equation 4.6.

$$t_{mean} = \frac{\int_{t_o}^{t_f} f(t)\,dt}{t_f - t_o} = \frac{\int_0^{60} 0\,dt + \int_{60}^{100}(100-t)\,dt}{100-0} = \frac{0 + \frac{40*40}{2}}{100-0} = 8s \tag{4.6}$$

Returning to equation 4.1, let's discuss how a new 'VA' event is added to the event list and determine the time at which it will occur. The moment of this event is calculated as the current clock time when a vehicle departs from a stop plus the trip time. The trip time is determined by considering both the time spent in motion, which is calculated using the distance between stops, and the time spent at junctions with traffic lights, which is determined based on the number of such junctions. However, it's important to note that a 'VA' event is not added to the event list when a vehicle leaves the last stop of the line since it means the vehicle is leaving the system.

Now, let's delve into how the 'VA' event affects the state variables and stats counters. Regardless of whether the stop is a single or double stop, and regardless of whether there are other vehicles in the stop, when a 'VA' event occurs at a stop, the vehicle is added to the queue of that stop (state variable). Furthermore, if the stop is empty (for single stops) or has only one vehicle in front (for double stops), a 'VR' (Vehicle Ready) event will be added to the event list. The details of how this event is added will be explained in its respective event section. Essentially, if there is available space at the stop to accommodate the alighting and boarding of passengers, these operations will commence immediately after the vehicle arrival. However, if there is insufficient space, the vehicle will remain waiting until another event triggers the start of the passengers' operations.

'VR' Event - Vehicle Ready:
The 'VR' event signifies the completion of passenger operations for a vehicle at a particular stop. It can be added to the event list in three situations: after a 'VA' event, after a 'VD' event or even after a proper 'VR' event. When a 'VA' event occurs and the stop is available, a 'VR' event is added to the list. The moment in the simulation when this event will transpire is determined by Equation 4.7, where the necessary time to perform passenger operations (t_{PO}) is added to the current clock time.

$$Clock_{VR} = Clock_{current} + t_{PO} \tag{4.7}$$

There is an additional scenario where the 'VR' event can occur after a 'VD' event. This situation arises when a vehicle that had a queue behind it finishes its passenger operations and departs from the stop, thus making the stop available again for the next vehicle in the queue.

The necessary time to perform passenger operations (t_{PO}) is calculated as a random number following a bounded normal distribution. The parameters of the bounded normal distribution, as shown in Table 4.3, are calculated using data from [20]. This data utilizes the dwell times of the 11 stops included in the study during peak hours on weekdays to determine the mean and standard deviation. The minimum and maximum values are used to establish the bounds of the

Distribution Parameter	Value [s]
Mean	24.12
Standard Deviation	4.62
Minimum	16.86
Maximum	32.51

Tab. 4.3: Bounded Normal Distribution Parameters extracted from data from [20]

normal distribution.

The 'VR' event possesses an additional attribute compared to the 'VA' event, which is the position within the stop where it occurs. In single stops, the position will always be the first since there is only one position available. However, in double stops, the position can be either the first or second. This differentiation is important because the order of vehicles within the stop can impact stop performance, as vehicles may block one another.

An example of a 'VR' event could be represented as $[115.12,'VR',2,7,1]$, indicating that a vehicle from line 2 that occupies the first position within the stop has completed its passenger operations at moment 115.12 in the simulation at stop 7.

The 'VR' event has implications for both the state variables and the statistics counters. There are various situations that can occur, and it can become quite complex. Thus, a detailed explanation is warranted.

The 'VR' event serves as a transition between the arrival of a vehicle and its departure from a stop. In an ideal scenario where the stop has infinite capacity and there are no traffic lights, a vehicle would leave immediately after completing passenger operations. However, in reality, at real stops, there is an intermediate state where the simulation checks if the necessary conditions are met for the vehicle to depart.

The simplest situation arises when the vehicle is ready in the first position of the stop (which is always the case for a single stop or the front position of a double stop). In this case, two scenarios can occur based on the state of the traffic light immediately after the stop. Situation A: If the traffic light is green, a 'VD' event is added to the events list at the exact same time as the 'VR' event. This signifies that the vehicle that is ready to leave can indeed depart. Situation B: Conversely, if the traffic light is red, the vehicle remains in its current position within the stop, waiting for another event to trigger its departure. Neither of these situations alters the state variables or the statistics counters. Both cases can be depicted in Figure 4.5.

When the ready vehicle is in the second position of the stop, the situation becomes more complicated. If there is no vehicle in the front position, it is referred to as a "ghost" car. This occurs when two vehicles arrive at the stop, and the vehicle in the front position departs. While there is technically an available space in the stop, it is not accessible to incoming vehicles because the vehicle in the second position is currently performing passenger operations and cannot move. Thus, there is a "ghost" vehicle occupying the first position.

When the vehicle in the second position is ready to leave, two scenarios can unfold based on the state of the traffic light. If the traffic light is green, a 'VD' event will be added to the

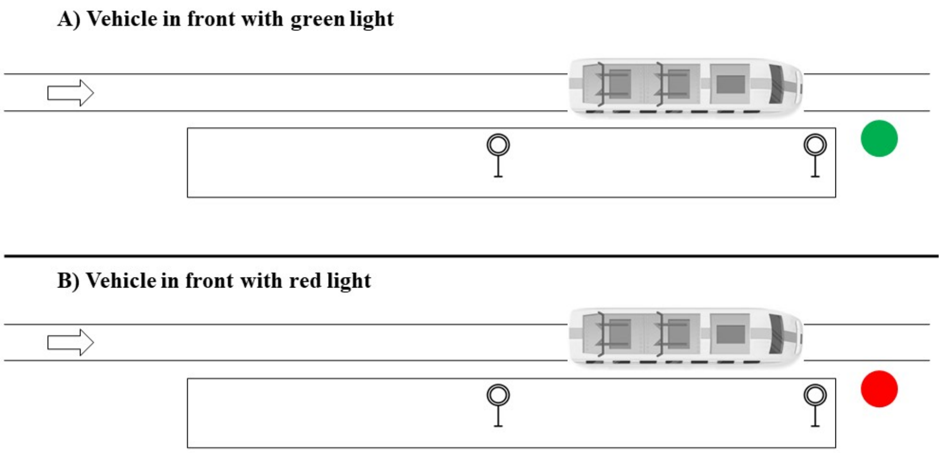

Fig. 4.5: 'VR' Event cases for vehicle at the front position of the stop

events list, similar to Situation A. This signifies that the vehicle can leave the stop. However, if the traffic light is red (Situation C), the vehicle in the second position will advance to the first position of the stop. Particularly, if there are vehicles queuing behind it, this allows the queued vehicles to begin performing passenger operations. In this case, the queue (a state variable) of the stop is modified by removing the "ghost" vehicle from the first position. Additionally, the '*waiting_time*' at that stop (a stats counter) is updated by adding the time difference between the clock moment when the queuing vehicle arrived to the stop and the current clock time. This ensures accurate tracking of waiting times at the stop.

To illustrate this situation, Figure 4.6 provides a visual representation of the before and after states of the stop, showcasing the presence of the "ghost" vehicle and its subsequent removal from the first position and also the updating of the stats counter.

Actually, this is the third remaining case when a 'VR' event is added to the events list, by another 'VR' event, because the vehicle that was queuing has now entered the stop and will proceed to complete the alighting and boarding of passengers. Additionally, starting from this point, whenever the '*waiting_time*' statistic counter is updated, it will be checked if the added time exceeds the '*max_waiting_time*' statistic counter. If it does, the '*max_waiting_time*' statistic counter will be updated accordingly to reflect the new maximum waiting time observed.

Lastly, there is a case where the ready vehicle is in the second position of the stop, but there is a vehicle in front of it, blocking the exit. In this scenario, regardless of the traffic light color, the vehicle remains in its current position and awaits another event to trigger its departure from the stop. The vehicle is unable to move until the blocking vehicle in the front position clears the exit.

'VD' Event - Vehicle Departure:

The 'VD' event represents the third type of event that can occur in the simulation. It signifies the moment when a vehicle, having completed the alighting and boarding of passengers, departs from a stop to proceed to the next stop or exit the system. This event is added to the events list

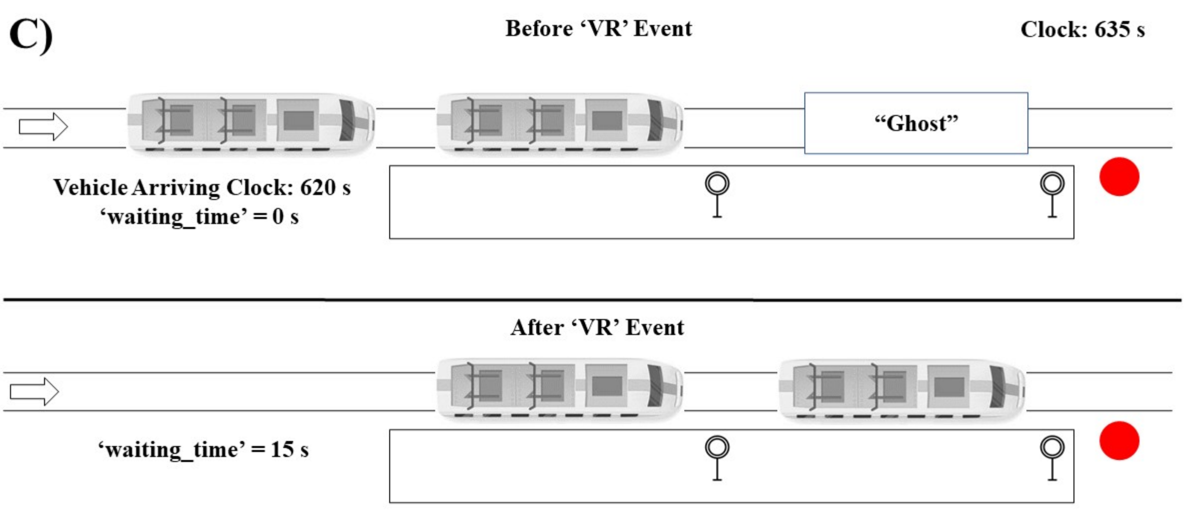

Fig. 4.6: Situation C. Before and after for a 'VR' Event when there is a vehicle queuing, the ready vehicle is in the second position, there is a "ghost" vehicle in the first one and a red light.

under two circumstances: after a 'VR' event, when a vehicle is ready to depart and there are no obstructions such as traffic lights or other vehicles blocking its exit from the stop, or after a 'TLG' (Traffic Light Green) event, indicating that the vehicle was ready to depart but was delayed by a traffic light. In both cases, the 'VD' event is added at the same clock time as the preceding 'VR' or 'TLG' event, as per Equation 1.

$$Clock_{VD} = Clock_{VR} = Clock_{TLG} \tag{4.8}$$

Now, let's consider how the 'VD' event affects the state variables and stats counters. Firstly, irrespective of other circumstances, a 'VA' event is added to the events list for the same line and at the next stop as the departing vehicle, provided that the vehicle is not leaving the last stop of the line. In the case of the last stop, no 'VA' event is added, as the vehicle is exiting the system.

Afterward, it must be checked if there are any vehicles queued behind the departing vehicle and whether this affects the simulation. In the case of single stops, if there is a vehicle in the queue behind the departing vehicle, that first vehicle in the queue enters the stop and begins its passenger operations, leading to the addition of a 'VR' event in the events list. Furthermore, similar to situation C, the '*waiting_time*' for that stop is updated, along with the '*n_waited_vehicles*' counter, as the newly arrived vehicle has experienced some waiting time. If no vehicles are queuing, the 'VD' event has no further implications.

However, if the departing vehicle is at a double stop, additional cases need to be considered based on the position of the vehicle's departure:

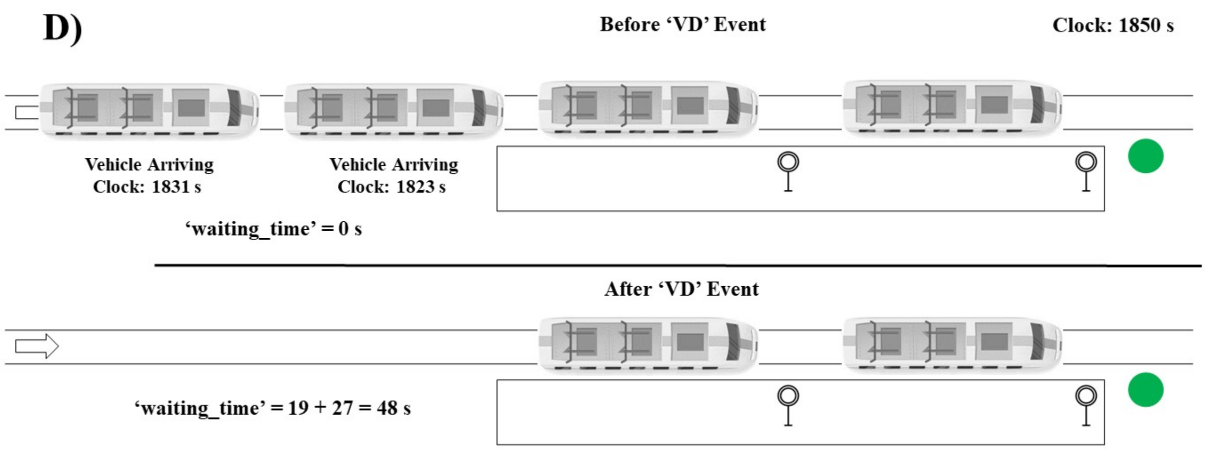

Fig. 4.7: Situation D. Two ready vehicles leave the stop, letting the next two enter the stop and updating the stats counters.

If the departure occurs from the first position of the stop, the simulation algorithm checks if there are any vehicles behind it. If so, it checks if the vehicle behind (i.e., the one in the second position of the double stop) is ready. If it is ready, the situation is the same as explained earlier. Both vehicles leave the stop, creating two additional empty spaces for passenger operations. If there are more vehicles queued behind them, they enter the stop, resulting in the addition of two 'VR' events and updating the corresponding '*waiting_time*' and '*n_waited_vehicles*' stats counters. This scenario (D) is depicted in Figure 4.7. However, if the vehicle behind is not ready, the departing vehicle leaves a '*ghost*' vehicle in the first position of the stop, as explained in the previous section. This situation (E) is depicted in Figure 4.8.

On the other hand, if the vehicle departs from the second position of the stop, it means there is a '*ghost*' vehicle in front of it, as determined in the previous iteration of the simulation. Despite this, the result is the same as in situation E; both the vehicle in the second position and the '*ghost*' vehicle leave, creating two vacant spaces at the stop. If there are more vehicles waiting, they are processed in the same manner as previously explained.

'TLG' Event - Traffic Light Green and 'TLR' Event - Traffic Light Red

The events discussed so far primarily control the movements of vehicles within the simulation. The remaining two event types are related to the management of traffic lights, enabling them to switch between green and red states. These events indirectly affect the vehicles in the simulation, depending on the circumstances at the stop, but not in a direct manner.

During the initialization of the simulation, all the necessary events related to traffic lights are predefined, eliminating the need to add any additional traffic light events while the simulation is running. However, these events can impact other parameters of the simulation during its execution.

The 'TLG' event, when triggered, switches the state of the traffic light at the corresponding stop from red to green, updating its state variable. Furthermore, this transition may have impli-

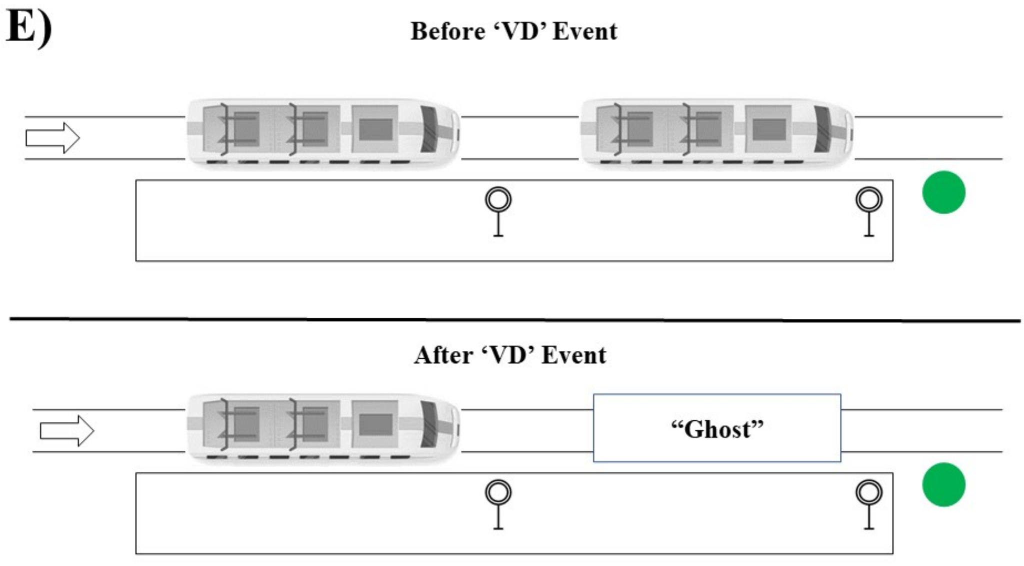

Fig. 4.8: Situation E. The ready vehicle departs from the stop leaving a '*ghost*' vehicle since the second one is not ready to depart.

cations if there are any ready vehicles waiting at that stop. In such cases, a 'VD' event is added at the same clock time as the 'TLG' event, as indicated by the previously mentioned Equation 4.8.

On the other hand, the 'TLR' event changes the traffic light state from green to red, preventing any vehicles from leaving the stop. This event serves the sole purpose of switching the traffic light state and does not have any further implications since vehicles cannot proceed when the traffic light is red.

With the description of the simulation's parameters, objects, and interactions complete, the simulation begins running, and the various objects start interacting, affecting state variables and updating statistical counters as the clock advances. Once the clock reaches the maximum simulation time (10800 seconds), the main simulation loop is stopped, and the dictionary containing information about the statistical counters is processed.

While the parameters '*n_vehicles*', '*n_waited_vehicles*', '*waiting_time*', and '*max_waiting_time*' are already determined by the end of the simulation, the following metrics will be calculated based on them:

- '*av_period*': This represents the average time between two vehicle arrivals at the stop. A lower value indicates a higher frequency of vehicle arrivals, while a higher value suggests fewer vehicles passing through. It is calculated according to Equation 4.9.
- '*av_queue*': This metric denotes the average length of the queue at the stop during the simulation. It is calculated using Equation 4.10.

- '*av_waiting_time*': This represents the average waiting time for a vehicle at the stop. It is calculated using Equation 4.11.
- '*av_waiting_time_among_waiters*': This metric indicates the average waiting time for vehicles that have waited at some point at the stop, providing a higher value. The equation for this metric is given by Equation 4.12.
- '*blocked_time*': This performance tracker measures the duration for which a vehicle at the second position of the stop is ready to depart but is blocked by the vehicle in front. This metric is updated during the simulation but was not explained in detail during the simulation's development due to its specialized nature.
- '*waiting_percentage*': This metric represents the percentage of vehicles that have waited at some point at the stop during the simulation. It is calculated using Equation 4.13.

$$av\_period = \frac{maxtime}{n\_vehicles} \tag{4.9}$$

$$av\_queue = \frac{waiting\_time}{maxtime} \tag{4.10}$$

$$av\_waiting\_time = \frac{waiting\_time}{n\_vehicles} \tag{4.11}$$

$$av\_waiting\_time\_among\_waiters = \frac{waiting\_time}{n\_waited\_vehicles} \tag{4.12}$$

$$waiting\_percentage = \frac{n\_waited\_vehicles}{n\_vehicles} \tag{4.13}$$

Finally, the $simulate(data)$ function returns the dictionary containing all these performance metrics for further analysis and evaluation.

4.4.5 Output Data - *write_results*

At this stage, the simulation has been executed, and the results are stored in a dictionary. To facilitate further analysis and experiments with this information, a function called $write\_results(df)$ has been developed. This function takes the output dictionary from the simulation, '*stops_data*', as input and saves it in a structured table format within an *.xlsx* file, similar to the format shown in Table 4.4 and 4.5. This allows for subsequent evaluations and analyses of the simulation results.

Stop	Stop Type	n lines	n vehicles	n waited vehicles	av period	waiting t
1	0	2	71	0	152.09	0
2	0	3	107	0	100.92	0
3	0	4	142	27	76.05	260.88
4	0	4	141	16	76.58	86.61
5	1	5	176	1	61.35	6.79
6	0	5	173	33	62.42	338.57
7	0	5	173	28	62.42	231.97
8	0	5	168	35	64.28	303.2
9	0	4	136	17	79.4	87.6
10	0	2	67	8	161.17	66.75
11	0	2	66	6	163.61	51
12	0	3	102	8	105.87	44.97
13	0	3	100	10	107.98	57.78
14	0	2	72	0	149.98	0

Tab. 4.4: Simulation Results 1

max waiting t	blocked t	av waiting time	av waiting t waiters	av queue	waiting %
0	0	0	0	0	0
0	0	0	0	0	0
25.76	0	1.84	9.66	0.02	0.19
15.13	0	0.61	5.41	0.01	0.11
6.79	1.33	0.04	6.79	0	0.01
23.08	0	1.96	10.26	0.03	0.19
23.59	0	1.34	8.28	0.02	0.16
27.52	0	1.8	8.66	0.03	0.21
22.46	0	0.64	5.15	0.01	0.13
24.6	0	1	8.34	0.01	0.12
24.8	0	0.77	8.5	0	0.09
13.76	0	0.44	5.62	0	0.08
17.13	0	0.58	5.78	0.01	0.1
0	0	0	0	0	0

Tab. 4.5: Simulation Results 2

Line Name	Trip Time Reality [min]	Trip Time Simulation [min]
D	12	12.02
1	17	17.08
2	14	14.07
71	12	12.20
U2Z	13	11.77

Tab. 4.6: Table Comparison for the trip time from the first to the last stop in each line between Reality and Simulation

4.5 Model Validation

In the final section of the simulation modeling, a validation of the model is necessary to assess the level of confidence in its results. There are two primary approaches employed to test the model.

4.5.1 Time Schedule Comparison

Firstly, it is important to acknowledge the limited availability of data pertaining to the system that the model aims to represent. Specifically, there is no recorded data regarding the precise timings of tram arrivals, passenger operations, and departures within Wiener Linien. However, information regarding the scheduled times for tram lines is accessible and can be utilized for validation purposes.

By employing the scheduled arrival times of tram vehicles at each stop, obtained from [16], the total trip time for a vehicle to travel from the first stop to the last stop can be calculated. Subsequently, once this trip time is determined for each vehicle, the simulation can provide the exact moment of departure for each vehicle at each stop, effectively generating a simulated time schedule. This allows for a direct comparison between the actual schedule and the simulated schedule to identify significant differences between reality and the simulation.

The comparison will be based on the total trip time required for each vehicle to traverse the entire line of stops. If the total trip times obtained from both reality and simulation exhibit close proximity, it can be inferred that the simulation is reasonably accurate, particularly with regard to time schedules.

The results for the described process can be seen in Table 4.6 and Figure 4.9:

To provide a clearer understanding of the process, it is essential to highlight that in the simulation, the sole parameter directly influencing the vehicle schedule is the line frequency, which determines the arrival of vehicles at the first stop of each line. Subsequently, the arrivals and departures at the remaining stops are entirely governed by the intrinsic rules and logic of the simulation, as previously described. In other words, the time schedules only regulate the input of vehicles into the simulation. Once vehicles enter the simulated tramway network, they navigate through the system based on the predetermined parameters such as passenger operation times, distances between stops, traffic lights, and other relevant factors. Eventually, vehicles exit the system.

Consequently, the time elapsed between the input and output of vehicles in the simulated tramway network is compared with the known real-world time schedules. The aim is to predict

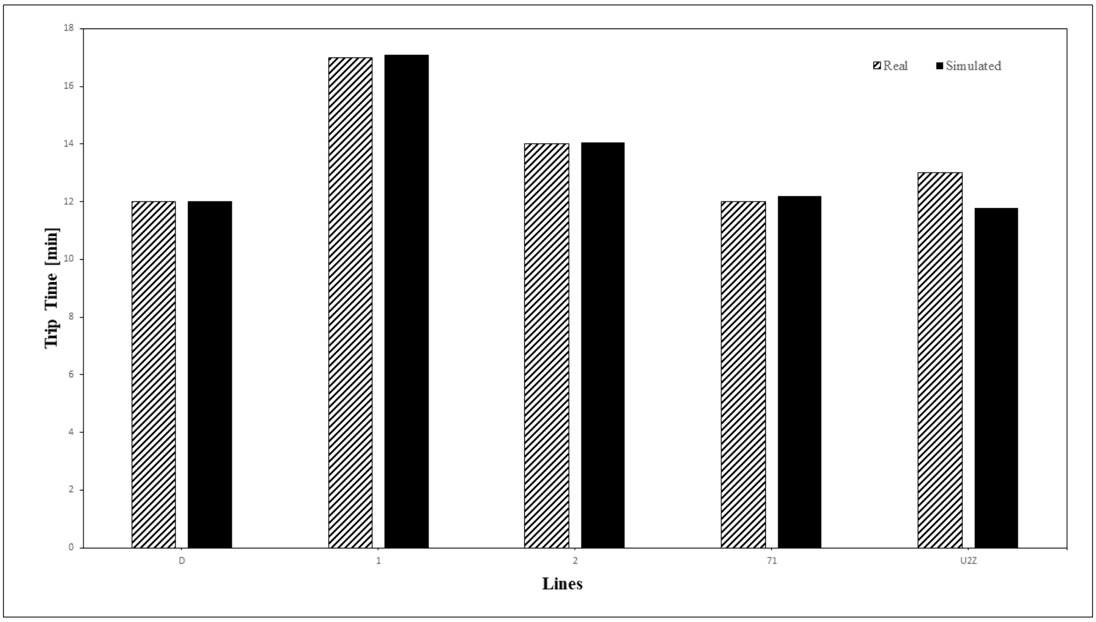

Fig. 4.9: Bar Chart Comparison for the trip time from the first to the last stop in each line between Reality and Simulation

outcomes that are already known, thereby evaluating whether the simulation behaves as expected.

In the majority of cases, the findings demonstrate promising results. The simulated trip times for the initial four lines (D, 1, 2, and 71) exhibit a high level of accuracy, closely resembling the actual trip durations observed in the real-world. However, a minor discrepancy arises in the case of line U2Z. This particular deviation was thoroughly discussed with the aforementioned experts at Wiener Linien, and it was concluded that the variance is not significant. It is important to note that line U2Z is a provisional service established to cater to the needs of a specific section of the U2 metro line currently undergoing construction. Consequently, this provisional nature is associated with a certain level of variability.

4.5.2 Simulation Visualization Tool

In addition to the previous validation approach, which primarily focuses on the simulation results, a visualization tool has been developed to allow users to observe the dynamic progression of the simulation and verify the functionality of the predefined rules.

The visualization tool features a screen that displays all the objects involved in the simulation and their respective state changes as the simulation unfolds. The simulation is paused by default, but pressing the space bar on the keyboard triggers the execution of the next event in the event list. This allows users to witness the impact of each event on the simulation's state.

The screen represents the 14 stops along the Vienna Ring with square-shaped icons, each displaying the corresponding stop's ID. Adjacent to each stop square, there is a circle representing the traffic light for that particular stop. The traffic light can be depicted as either green or red, indicating its current state. The top left corner of the screen presents the simulation's current clock time, as well as the details of the recently executed event and the upcoming event. These

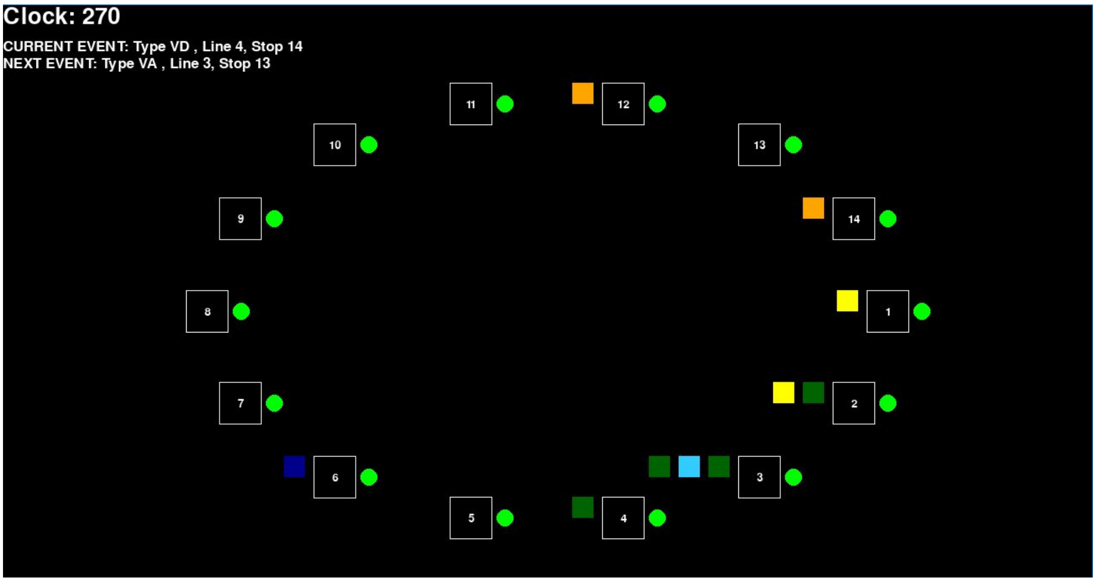

Fig. 4.10: Visualization Tool Example

event characteristics include the event clock, type, line, and stop.

Furthermore, when a vehicle arrives at a stop, a square is displayed to the left of the corresponding stop square, representing the vehicle queue. Each line is assigned a distinct color, allowing for differentiation between vehicles from different lines (e.g., dark green, light blue, dark blue, orange and yellow). When a vehicle is ready to depart, its color transitions from the line's designated color to light green. Once it actually departs, the vehicle disappears from the screen. This visual representation enables users to observe the development of queues and assess whether the simulation model behaves as expected, in accordance with the defined events, across various scenarios. In Figure 4.10 an example of the visualization tool can be seen.

Chapter 5

Simulation Experiment and Analyses

This chapter presents the design of the simulation experiment, which involves applying changes to the input data to identify the factors influencing the simulation's behavior.

5.1 Selection of Appropriate Experimental Design

Relevant performance measures for the simulation need to be chosen. In this regard, two measures have been selected.

The primary focus is to examine the extent to which double stops can increase the capacity of a tramway network. However, a crucial question arises: How do we define capacity? [21] provides a comprehensive explanation and examples of various capacity terms, including passenger capacity of a vehicle, vehicle capacity of a route, passenger capacity of a station and station capacity for interface with personal transport modes. Ultimately, the capacity of a tramway network can be defined as the ability to transport passengers over a given distance per unit of time $[\frac{pass*dist}{time}]$. This definition incorporates all the previously suggested capacity definitions.

The goal of this thesis is to explore how and to what extent the implementation of double stops can enhance the defined capacity. It is important to note that double stops do not directly increase the number of passengers per vehicle or accelerate the movement of vehicles on the railways. Rather, the factor that double stops can influence is time - specifically, the time required to transport a passenger from point A to point B. By reducing dwell time through the implementation of double stops, the tramway network's capacity can be increased. Hence, the performance indicator that needs to be studied in the simulation is the vehicle frequency at each stop or, conversely, the Average Period between vehicles, which is the first selected statistical measure.

Double stops can also help alleviate another problem that can arise in a tramway network: waiting time at stops. When a tramway stop is fully occupied and a new vehicle arrives, it must wait outside the stop. This situation can lead to traffic congestion, particularly if the stop is located after a traffic junction. Therefore, it is crucial to measure the impact of waiting time, and thus, the total Waiting Time at each stop will be monitored. From a capacity perspective, it is also valuable to investigate any correlation between the Average Period and the total Waiting Time at each stop.

5.2 Establishment of Experimental Conditions for Runs

In this section, the conditions under which the simulation will be conducted and the number of simulation runs will be determined. There will be three different situations considered:

- Real Conditions. In this scenario, the simulation will utilize real data as input. The actual tramway network data, including stop configurations, will be used to simulate the system under realistic conditions.
- Single Conditions. In this case, all stops in the simulation will be modified to represent single stops. This scenario aims to simulate the worst-case scenario, where each stop consists of a single platform.
- Double Conditions. Conversely, in this scenario, all stops in the simulation will be adjusted to represent double stops. This setup represents the best-case scenario, where each stop is equipped with two platforms.

By considering these three different conditions, we can establish both a lower and an upper limit for the simulation outcomes. Additionally, the results obtained from the real conditions simulation can be compared to these limits to evaluate the system's performance.

In order to determine the number of times the simulation will be run, it is important to consider the stochastic nature of the simulation. As the simulation incorporates probability distributions for various factors, running the simulation only once for each case would not provide sufficient data to draw reliable conclusions or make informed decisions.

Given the inherent variability in the simulation outcomes, it is necessary to run the simulation multiple times to obtain a large enough sample size. This enables the data to be associated with a known distribution, facilitating further statistical analyses such as confidence intervals, t-tests and ANOVA.

As a first step, 100 simulations were executed, and the results for the Average Periods and Waiting Times of each stop were stored in a dataframe. The dataframe consists of 28 columns (representing the Average Period and Waiting Time for the 14 stops of the Vienna Ring) and 100 rows, where each row corresponds to the results of one simulation.

Upon analyzing the data, two distinct behaviors are observed. For the Average Periods of all stops, the results are centered around the same value, exhibiting insignificant variance. The average standard deviation for the sample, ranging from 70 to 360 seconds, is merely 0.137 seconds. Consequently, there is no need to associate the Average Period measurements with any distribution due to the negligible variance.

However, the Waiting Time results display greater variability. Figure 5.1 depicts 14 histograms, one for each stop's Waiting Time. Given this variability, it is worthwhile to investigate if the datasets can be associated with a normal distribution. To assess this, a normality test is performed, specifically the Shapiro-Wilk Test.

The Shapiro-Wilk test is a statistical test used to determine whether a given dataset follows a normal distribution. It is chosen due to its robustness and ability to handle small to moderate

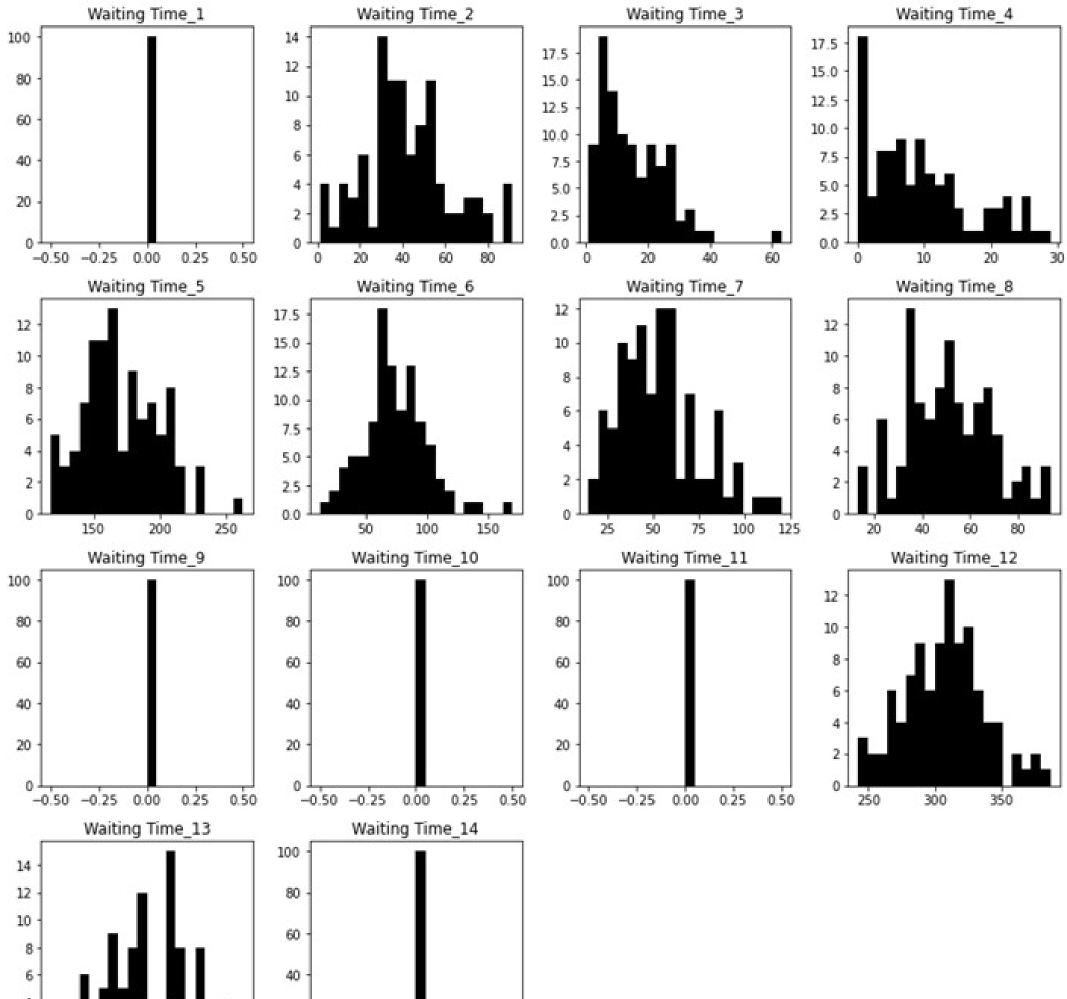

Fig. 5.1: Histograms for the Waiting Times in the 14 stops

sample sizes. The test calculates a test statistic (W) and compares it to critical values to evaluate the departure from normality. The process for conducting the Shapiro-Wilk test is as follows:

- Define the null and alternative hypotheses:
  - Null hypothesis (H0): The data is normally distributed.
  - Alternative hypothesis (H1): The data is not normally distributed.
- Calculate the test statistic (W) using the Shapiro-Wilk formula 5.1, which involves sample size (n) and coefficients (a and b) derived from the covariances of the ordered sample values
- Calculate the p-value associated with the test statistic. The p-value represents the probability of observing data as extreme as, or more extreme than, the actual sample if the null hypothesis is true.
- Compare the calculated p-value to a predetermined significance level (alpha) (e.g., 0.05). If the p-value is less than alpha, reject the null hypothesis and conclude that the data is not normally distributed. If the p-value is greater than or equal to alpha, fail to reject the null hypothesis and conclude that the data is normally distributed.

$$W = \frac{\left(\sum_{i=1}^{n} a_i x_{(i)}\right)^2}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{5.1}$$

The results of the normality test are presented in Table 5.1.

Stop Name	Stop ID	p-value	Normal
Schottenring	1	-	YES
Börse	2	0.3205	YES
Schottentor	3	0.000	NO
Rathauspl., Burgtheater	4	0.0140	NO
Parlament	5	0.2129	YES
Ring, Volkstheater	6	0.0070	NO
Burgring	7	0.0129	NO
Oper, Karlsplatz	8	0.5205	YES
Schwarzenbergpl.	9	-	YES
Weihburgg.	10	-	YES
Stubentor	11	-	YES
Julius-Raab-Pl.	12	0.7448	YES
Schwedenpl.	13	0.5036	YES
Salztorbr.	14	-	YES

Tab. 5.1: Shapiro-Wilk Normality Test for the 14 Waiting Times

The significance level for comparing the p-value is set at 0.05, indicating that if the p-value is lower than this threshold, the probability of the null hypothesis being true is so low that it must be rejected, implying that the data is not normally distributed.

Analyzing the results from Table 5.1, it can be observed that a significant portion of the Waiting Times follow a normal distribution. For stops 1, 9, 10, 11, and 14, there is no need to further investigate the normality of the data since all the values are centered around 0. However, for stops 3, 4, 6, and 7, the null hypothesis of normality is rejected. For the remaining stops, the null hypothesis is accepted, suggesting a normal distribution.

Although it is found that most of the stops exhibit a normal distribution or deterministic behavior, there are exceptions. This could pose challenges when analyzing the results of the experiment. To address this issue, the Central Limit Theorem (CLT) can be applied.

The CLT is a fundamental concept in probability theory and statistics. It states that under certain conditions, the average of a large number of independent and identically distributed random variables will tend to follow a normal distribution, regardless of the shape of the original distribution.

In simpler terms, the CLT implies that if a large number of random samples are taken from a population with a finite mean and variance, and the mean of each sample is calculated, those sample means will be approximately normally distributed, irrespective of the original population's shape.

The CLT enables us to make inferences about a population based on a sample. Even if the exact shape of the population distribution is unknown, we can rely on the normal distribution approximation for sample means.

The conditions for the CLT to hold are as follows:

- Independence: The random variables in the sample should be independent of each other. The value of one random variable should not provide any information about the values of other random variables.
- Identical distribution: Each random variable should be drawn from the same distribution, meaning they should have the same mean and variance.
- Sample size: The sample size should be sufficiently large. While there is no fixed threshold for "sufficiently large," a general guideline is a sample size of 30 or more, although larger sample sizes yield better approximations to a normal distribution.

To obtain a normal distribution for the Waiting Times, a specific approach has been taken. The simulation has been run 30 times, and for each stop, the mean of the Waiting Times has been calculated. This process has been repeated 100 times to gather the data. The resulting histograms, depicting the distribution of the sample means, can be seen in Figure 5.3. Furthermore, a normality test has been performed on the collected data, and the results are presented in Table 5.2.

Having selected the appropriate indicators for the simulation and established the experimental conditions, the next step is to execute the simulation based on the explained.

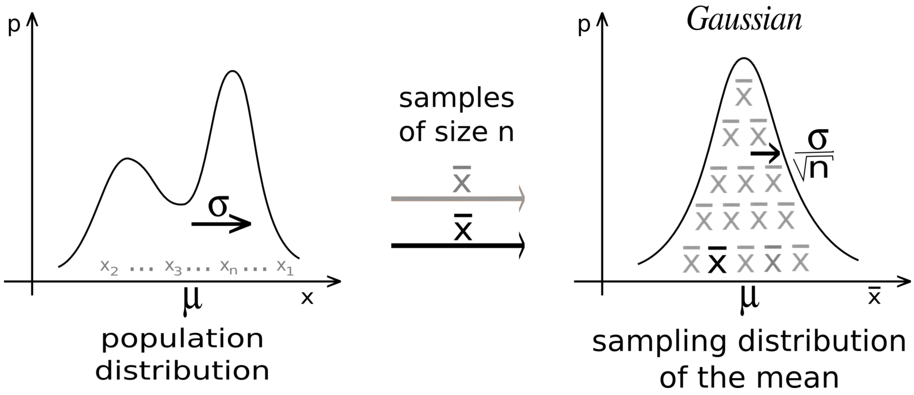

Fig. 5.2: Illustration Central Limit Theorem extracted from [22]

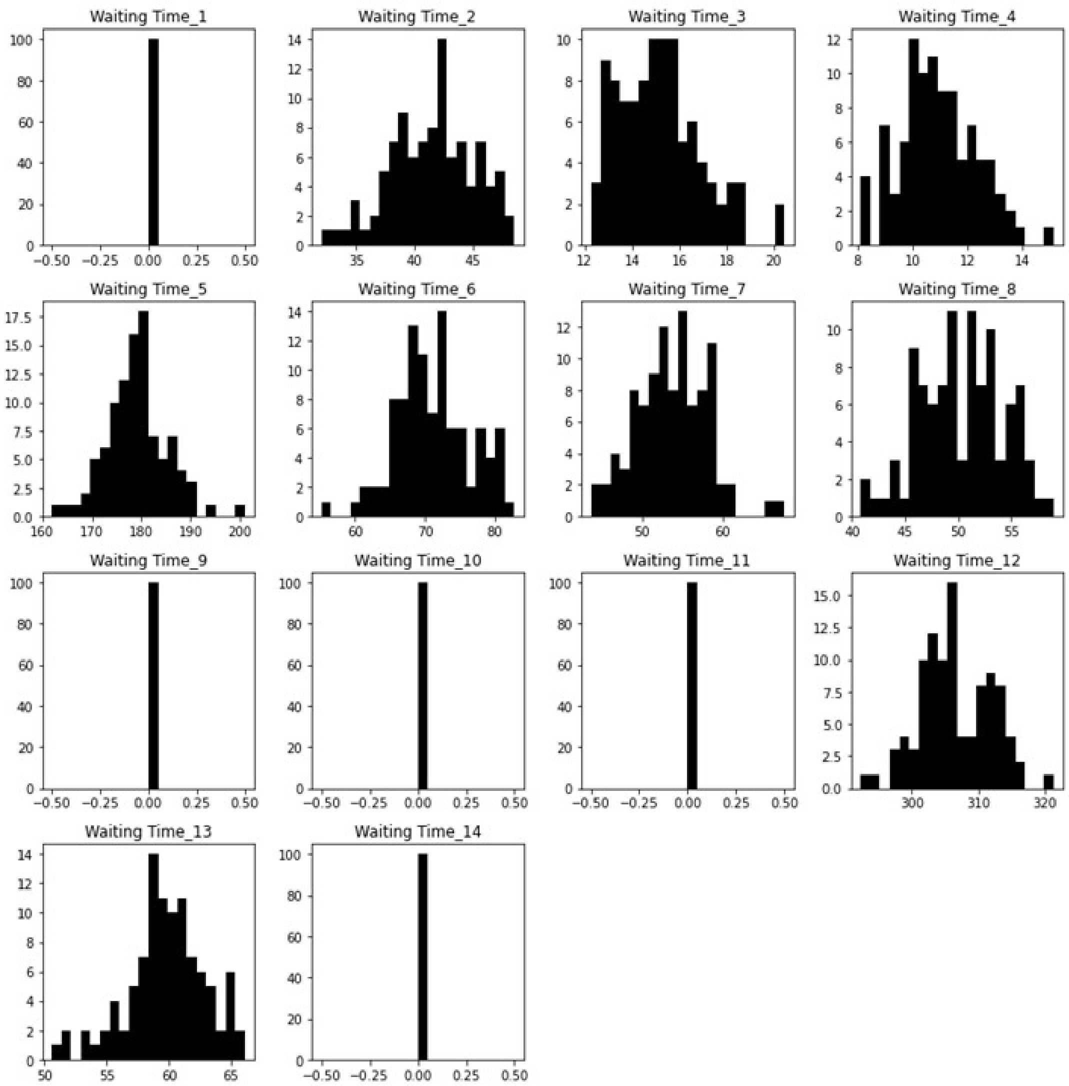

Fig. 5.3: Histograms for the Waiting Times in the 14 stops with the CLT applied

Stop Name	Stop ID	p-value	Normal
Schottenring	1	-	YES
Börse	2	0.4730	YES
Schottentor	3	0.1176	YES
Rathauspl., Burgtheater	4	0.9652	YES
Parlament	5	0.3212	YES
Ring, Volkstheater	6	0.4250	YES
Burgring	7	0.4903	YES
Oper, Karlsplatz	8	0.5181	YES
Schwarzenbergpl.	9	-	YES
Weihburgg.	10	-	YES
Stubentor	11	-	YES
Julius-Raab-Pl.	12	0.3500	YES
Schwedenpl.	13	0.7674	YES
Salztorbr.	14	-	YES

Tab. 5.2: Shapiro-Wilk Normality Test for the 14 Waiting Times with the CLT applied

5.3 Simulation Analyses

5.3.1 Analyses for the Average Periods

Table 5.3 presents the simulation results for the Average Periods' means in each stop, obtained through the implementation of the Central Limit Theorem (CLT) when utilizing real stops, treating all stops as single entities and considering all stops as double entities.

The analysis of the simulation results reveals that the transition from single stops to double stops does not significantly affect the average period of vehicles passing through the stops or the overall capacity of the tramway network. This finding may seem surprising since it is intuitive to expect that double stops would increase capacity by allowing for the processing of two vehicles at a time. However, in the case of the Vienna Ring tramway network, the stops are not saturated enough to observe a noticeable effect of double stops on capacity.

To gain a better understanding of this observation, each stop can be considered as a M/M/1 queue system. In queueing theory, an M/M/1 queue represents a queue in a system with a single server, where arrivals are determined by a Poisson process and job service times follow an exponential distribution. Although the arrival process and service times in the tramway system may not strictly follow Poisson and exponential distributions, average values can be used for analysis purposes. A representation of an M/M/1 queue can be seen in Figure 5.4.

Fig. 5.4: Representation of a M/M/1 queueing system from [23]

Stop	Stop ID	Real	Single	Double
Schottenring	1	189.42	189.43	189.42
Börse	2	92.28	92.28	92.28
Schottentor	3	92.28	92.28	92.28
Rathauspl., Burgtheater	4	92.40	92.48	92.41
Parlament	5	74.00	74.45	74.00
Ring, Volkstheater	6	73.45	73.45	73.45
Burgring	7	73.52	73.53	73.52
Oper, Karlsplatz	8	73.96	74.29	73.96
Schwarzenbergpl.	9	121.51	121.51	121.51
Weihburgg	10	359.90	359.91	359.91
Stubentor 11	11	359.90	359.91	359.91
Julius-Raab-Pl.	12	180.05	181.21	180.03
Schwedenpl	13	179.95	179.95	179.95
Salztorbr.	14	359.90	359.91	359.91

Tab. 5.3: Average Periods' means for each stop for real, all single and all double conditions

The arrival rate (λ) represents the average number of units (vehicles) arriving at a particular point in the system per unit of time, while the service rate (μ) represents the average number of units the system can process at that point per unit of time. In a stable queueing system, the service rate must be higher than the arrival rate to prevent the queue from growing indefinitely ($\mu > \lambda$). However, due to probabilistic variability, even if the service rate is higher than the arrival rate, queues may still occur but will eventually dissipate or reach a steady state.

Comparing the arrival rate to the service rate provides an indication of how saturated the system is. The ratio of the arrival rate to the service rate represents the average proportion of time the server (stop) is occupied, it can be called buffer utilization ($\rho = \frac{\lambda}{\mu}$). A value close to 1 indicates that the server is highly occupied, increasing the likelihood of queues forming. Conversely, a value closer to 0 suggests that the server is underutilized, reducing the probability of queues.

For the Vienna Ring case, the arrival rate can be computed using Equation 5.2, which incorporates the number of lines traversing each stop and the respective time period for each line. Simultaneously, the service rate can be readily determined due to the known average time required for passengers to alight and board a vehicle (24.12 s). The computations for these parameters are presented in Table 5.4.

$$\lambda_i = \sum_{j=1}^{n_i} \frac{1}{Lf_{ij}} \tag{5.2}$$

i: stop identification that ranges from 1 to 14.
j: line identification in the stop that ranges from 1 to n.
n_i: number of lines that pass through that particular stop
Lf_{ij}: line frequency at the stop i in line j [s/vehicle].

Stop	Stop ID	Number of lines	λ [vehicles/s]	λ [s/vehicle]	μ [vehicle/s]	μ [s/vehicle]	ρ
Schottenring	1	2	0.005	189.474	0.0415	24.12	0.1273
Börse	2	4	0.011	92.308	0.0415	24.12	0.2613
Schottentor	3	4	0.011	92.308	0.0415	24.12	0.2613
Rathauspl., Burgtheater	4	4	0.011	92.308	0.0415	24.12	0.2613
Parlament	5	5	0.014	73.469	0.0415	24.12	0.3283
Ring, Volkstheater	6	5	0.014	73.469	0.0415	24.12	0.3283
Burgring	7	5	0.014	73.469	0.0415	24.12	0.3283
Oper, Karlsplatz	8	5	0.014	73.469	0.0415	24.12	0.3283
Schwarzenbergpl.	9	3	0.008	120.000	0.0415	24.12	0.201
Weihburgg	10	1	0.003	360.000	0.0415	24.12	0.067
Stubentor 11	11	1	0.003	360.000	0.0415	24.12	0.067
Julius-Raab-Pl.	12	2	0.006	180.000	0.0415	24.12	0.134
Schwedenpl	13	2	0.006	180.000	0.0415	24.12	0.134
Salztorbr.	14	1	0.003	360.000	0.0415	24.12	0.067

Tab. 5.4: Arrival (λ) and service (μ) rates for all the stops. As well as the utilization factor (ρ).

Based on this information, the utilization factor (ρ) can be calculated, revealing two significant observations. Firstly, it demonstrates the efficacy of the steady model in describing the simulation behavior, as evidenced by the nearly identical results for the average period and arrival rate (expressed in seconds per vehicle), as can be seen in Table 5.5. However, it is important to note that this steady model exclusively characterizes the behavior of single stops.

Stop	Stop ID	Real	Single	Double	Arrival Rate (λ)
Schottenring	1	189.42	189.43	189.42	189.47
Börse	2	92.28	92.28	92.28	92.31
Schottentor	3	92.28	92.28	92.28	92.31
Rathauspl.. Burgtheater	4	92.40	92.48	92.41	92.31
Parlament	5	74.00	74.45	74.00	73.47
Ring, Volkstheater	6	73.45	73.45	73.45	73.47
Burgrin	7	73.52	73.53	73.52	73.47
Oper, Karlsplatz	8	73.96	74.29	73.96	73.47
Schwarzenbergpl.	9	121.51	121.51	121.51	120.00
Weihburgg	10	359.90	359.91	359.91	360.00
Stubentor 11	11	359.90	359.91	359.91	360.00
Julius-Raab-Pl.	12	180.05	181.21	180.03	180.00
Schwedenpl	13	179.95	179.95	179.95	180.00
Salztorbr.	14	359.90	359.91	359.91	360.00

Tab. 5.5: Comparison between the Average Periods from the simulation and the Arrival rate (λ) calculated using 5.2.

Secondly, the analysis highlights the relatively low occupancy of the stops. Even in the worst-case scenario, wherein a stop is frequented by five distinct lines, the occupancy rate merely reaches 33%. Consequently, given the current occupancy level, there appears to be no pressing need to convert single stops into double stops. Despite the possibility of increased network capacity, the overall behavior is not anticipated to change in terms of productivity.

However, drawing the sole conclusion that the Vienna Ring does not require double stops due to its underloaded nature would be an oversimplified assessment. Instead, it is more meaningful to explore the following question: What is the maximum load that the tramway network can accommodate using only single stops without compromising stop performance? Furthermore, what occurs when the load continues to increase for both single and double stop scenarios?

To address these inquiries, the approach involves assuming an equal line frequency for all tram lines. Subsequently, the line frequency necessary to achieve utilization factors of 30%, 40%, 50%, and so forth, up to 120% at intervals of 10%, will be calculated for stops 5 to 8, which are served by five lines. The respective line frequencies, as derived from this analysis, are presented in Table 5.6.

In order to ensure good performance of a stop, it is crucial for the Average Period obtained from the simulation, which represents the departure rate of vehicles, to be equal to or very close to the Arrival Rate. This implies that the service capacity does not cause any disruptions or delays at the stop. The Average Period should never exceed the Arrival Rate, as that would imply more vehicles leaving the stop than entering, which is not feasible. Consequently, the Arrival Rate will be considered as the benchmark for maximum efficiency, and the deviation

Utilization Factor (ρ)	Line Frequency [s/vehicle]	Arrival Rate (λ) [s/vehicle]
30%	402.0	80.4
40%	301.5	60.3
50%	241.2	48.2
60%	201.0	40.2
70%	172.3	34.5
80%	150.8	30.2
90%	134.0	26.8
100%	120.6	24.1
110%	109.6	21.9
120%	100.5	20.1

Tab. 5.6: Lines Frequencies and Arrival Rates at stops with 5 lines for different Utilization Factors

of the simulated Average Period (AP) from this maximum efficiency point will be utilized to calculate the stop's efficiency using Equation 5.3.

$$Eff = \frac{\frac{1}{AP}}{\frac{1}{\lambda}} \tag{5.3}$$

For this analysis, the Simulated Average Period used is the average for the four stops through which five different lines pass. These stops exhibit the highest arrival rates and are of particular interest. The experimental results are presented in Table 5.7, while Figure 5.5 illustrates the outcomes through a line chart.

Rho	**Arrival Rate**	**Simulated Average Period Single**	**Simulated Average Period Double**	**Efficiency Single**	**Efficiency Double**
0.3	80.4	81.11	81.05	99.13%	99.19%
0.4	60.3	61.55	61.40	97.97%	98.21%
0.5	48.24	49.59	49.47	97.28%	97.52%
0.6	40.2	41.58	41.50	96.68%	96.87%
0.7	34.46	34.73	31.29	86.80%	96.34%
0.9	26.8	34.42	27.85	77.85%	96.23%
1.0	24.12	34.56	25.12	69.79%	96.00%
1.1	21.93	34.45	22.92	63.66%	95.68%
1.2	20.1	34.57	21.07	58.15%	95.40%

Tab. 5.7: Simulation Results

The results reveal some interesting insights. At a Utilization Factor of 0.3, which closely resembles the actual conditions, both the single and double stop systems exhibit similar levels of efficiency. This trend persists as the Utilization Factor increases, until it reaches 0.7. At this point, the system with single stops exhibits a distinct change in its efficiency trajectory. As the Utilization Factor continues to rise, the efficiency of the single stop system declines at a higher rate compared to earlier stages. Conversely, the system with double stops maintains a relatively

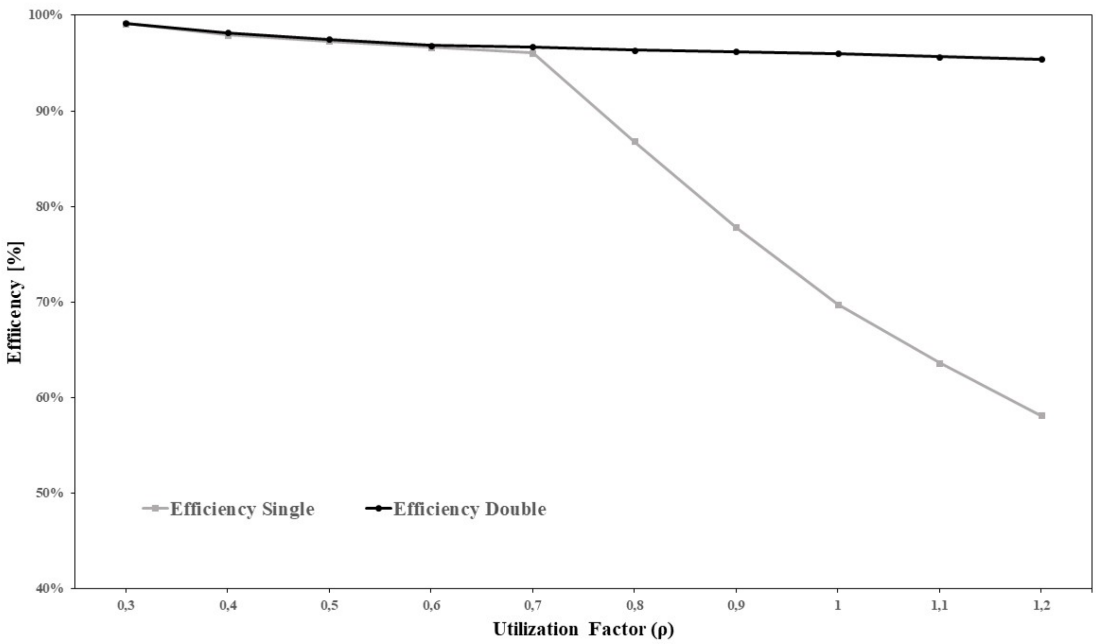

Fig. 5.5: Line chart of the stops Efficiency for a different Utilization Factors

constant level of efficiency, even for Utilization Factors exceeding 1.

From these findings, two key observations can be made. Firstly, the notion of a "Saturation Point" can be defined. The Saturation Point represents the maximum Utilization Factor that a system can sustain without experiencing a significant decrease in efficiency. Beyond this point, the system's stops become incapable of effectively managing the Arrival Rate, resulting in indefinite queue growth and a substantial decrease in stop efficiency.

Considering that the Saturation Point for the single stop system is at 0.7, it implies that the maximum Arrival Rate (λ) that the system stops can handle efficiently is 70% of the Service Rate (μ). In other words, for the single stop system to operate efficiently, specifically in the Vienna Ring case, the following condition must hold true: $\lambda \leq 0.7\mu$.

The remaining question to address is the location of the Saturation Point for the system with only double stops. To answer this question, a similar experiment can be conducted, but with higher Utilization Factors ranging up to 2.0. The results of this analysis are depicted in Figure 5.6.

Interestingly, it is found that the Saturation Point for the system with double stops is at 1.4, exactly double that of the single stop system. This observation is significant because it signifies that, at least in the case of the Vienna Ring, double stops effectively double the capacity of single stops. Consequently, in order for the system to operate without compromising its efficiency, the following rule must be adhered to: $\lambda \leq 1.4\mu$.

Lastly, it is worth visualizing another intriguing chart that depicts how the Average Period, measured in vehicles per minute, at stops with five lines increases in tandem with the Utilization Factor. The results reveal that the average period grows proportionally at the same rate as the Utilization Factor, following a nearly linear relationship. However, once the stops reach their respective saturation points (0.7 for the single stop case and 1.4 for the double stop case), the

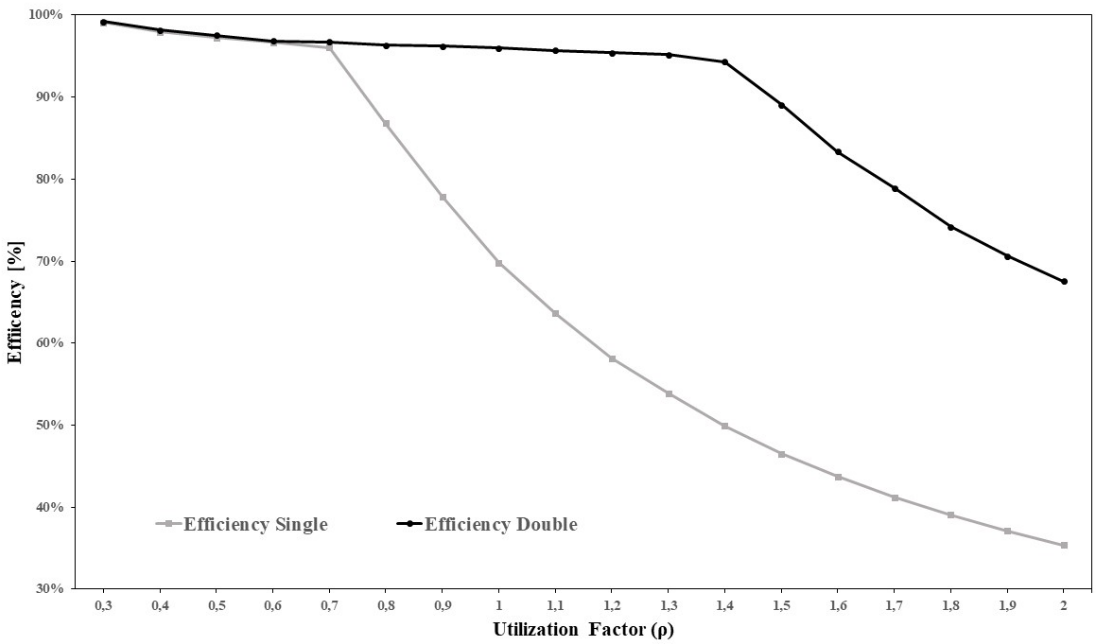

Fig. 5.6: Line chart of the stops Efficiency for a different Utilization Factors

Average Period ceases to increase. This occurs because the service rate at each stop becomes unable to accommodate a higher frequency of vehicles.This visualization can be seen in Figure 5.7

5.3.2 Analyses for the Waiting Times

As mentioned previously, the total Waiting Time at each stop is another parameter tracked in the simulations. Waiting Time is a crucial factor in the proper functioning of a stop, as having a vehicle outside the stop waiting to enter can potentially lead to traffic congestion or blocking, depending on the physical structure of the stop. Therefore, it can serve as a valuable criteria for sizing the network.

Similar to the previous experiment, Table 1 presents the simulation results for the mean Waiting Times at each stop. These results were obtained by applying the Central Limit Theorem (CLT) under three conditions: utilizing real stops, treating all stops as single stops, and considering all stops as double stops.

The data clearly demonstrates that the number of double stops has a significant impact on the total amount of waiting time experienced at each stop. In the best-case scenario, where all stops are double stops, the total waiting time is 437 seconds. The real scenario, which already incorporates a considerable number of double stops, yields a slightly higher total waiting time of 788 seconds. Conversely, the worst-case scenario, where all stops are single, exhibits a substantial increase in total waiting time, amounting to 2791 seconds.

A promising approach to address this issue is to start with the scenario where no double stops are present and aim to minimize the total Waiting Time by converting the minimum number of

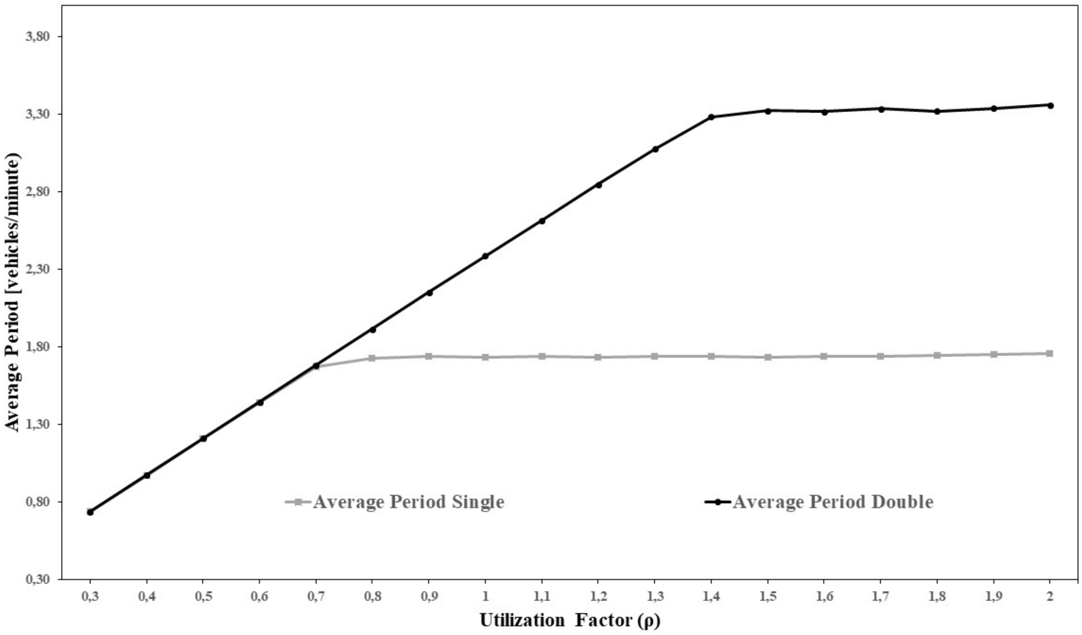

Fig. 5.7: Line chart of the Average Period for a different Utilization Factors

Stop	**Stop ID**	**Real** [s]	**Single** [s]	**Double** [s]
Schottenring	1	0.00	30.22	0.00
Börse	2	41.52	417.82	56.80
Schottentor	3	15.17	119.16	17.62
Rathauspl., Burgtheater	4	10.93	80.78	12.38
Parlament	5	179.18	835.80	171.18
Ring, Volkstheater	6	71.18	319.63	72.25
Burgring	7	53.68	225.93	55.96
Oper, Karlsplatz	8	50.34	374.85	51.30
Schwarzenbergpl.	9	0.00	22.83	0.00
Weihburgg	10	0.00	0.00	0.00
Stubentor 11	11	0.00	0.00	0.00
Julius-Raab-Pl.	12	306.42	304.12	0.00
Schwedenpl	13	59.76	60.01	0.00
Salztorbr.	14	0.00	0.00	0.00
Total	**-**	**788.18**	**2791.14**	**437.49**

Tab. 5.8: Waiting Time's means for each stop for real, all single and all double conditions

single stops into double stops. In other words, the focus is on prioritizing the stops that have the most significant impact on the system initially, while leaving the less impactful stops for later consideration. Since implementing changes such as converting a stop from single to double may involve costs (e.g., construction, time, passenger inconvenience during the transition), it is reasonable to maximize the benefits obtained from the initial changes and address the remaining stops if necessary.

The question that arises now is: what criteria should be used to determine the optimal stop conversion sequence? An intuitive approach could be to convert the stop with the highest Waiting Time from single to double, as reducing the Waiting Time at that particular stop would likely yield substantial improvements. Examining the results from Table 5.8, it is evident that stop number 5 is the most affected stop, with over 800 seconds of Waiting Time. Consequently, a new simulation has been conducted, maintaining the same conditions as previously explained (application of the Central Limit Theorem to ensure mean normality) but considering all stops as single except for stop number 5, which is designated as a double stop. The simulation results are presented in the comparative Table 5.9, while Figures 5.8 and 5.9 depict the situations for both conditions.

Stop	**Stop ID**	**Number of lines**	**All Single** [s]	**All Single but 5** [s]
Schottenring	1	2	30.2	29.6
Börse	2	4	417.8	441.1
Schottentor	3	4	119.2	111.0
Rathauspl., Burgtheater	4	4	80.8	73.9
Parlament	5	5	835.8	127.7
Ring, Volkstheater	6	5	319.6	814.7
Burgring	7	5	225.9	234.9
Oper, Karlsplatz	8	5	374.9	339.3
Schwarzenbergpl.	9	3	22.8	24.9
Weihburgg	10	1	0.0	0.0
Stubentor 11	11	1	0.0	0.0
Julius-Raab-Pl.	12	2	304.1	311.0
Schwedenpl	13	2	60.0	60.2
Salztorbr.	14	1	0.0	0.0
Total	**-**	**-**	**2791.1**	**2568.3**

Tab. 5.9: Waiting Time's means for each stop for all stops single conditions and all single but stop 5.

Comparing the results reveals an interesting insight. Changing stop number 5 from single to double has indeed led to a significant improvement in the Waiting Time at that particular stop, decreasing from 835.8 seconds to 127.7 seconds, resulting in a difference of 708.1 seconds. However, the overall reduction in total Waiting Time is only 222.9 seconds. This prompts the question: Have the Waiting Times at other stops increased as a result of the change in stop 5? The answer is yes.

Notably, stop number 6, which follows stop 5 along the Vienna Ring route, has experienced an increase in Waiting Time. Figure 5.8 illustrates that stop 5 serves as the entry point to the zone of the Vienna Ring with the highest load, where a substantial portion of the total Waiting Time

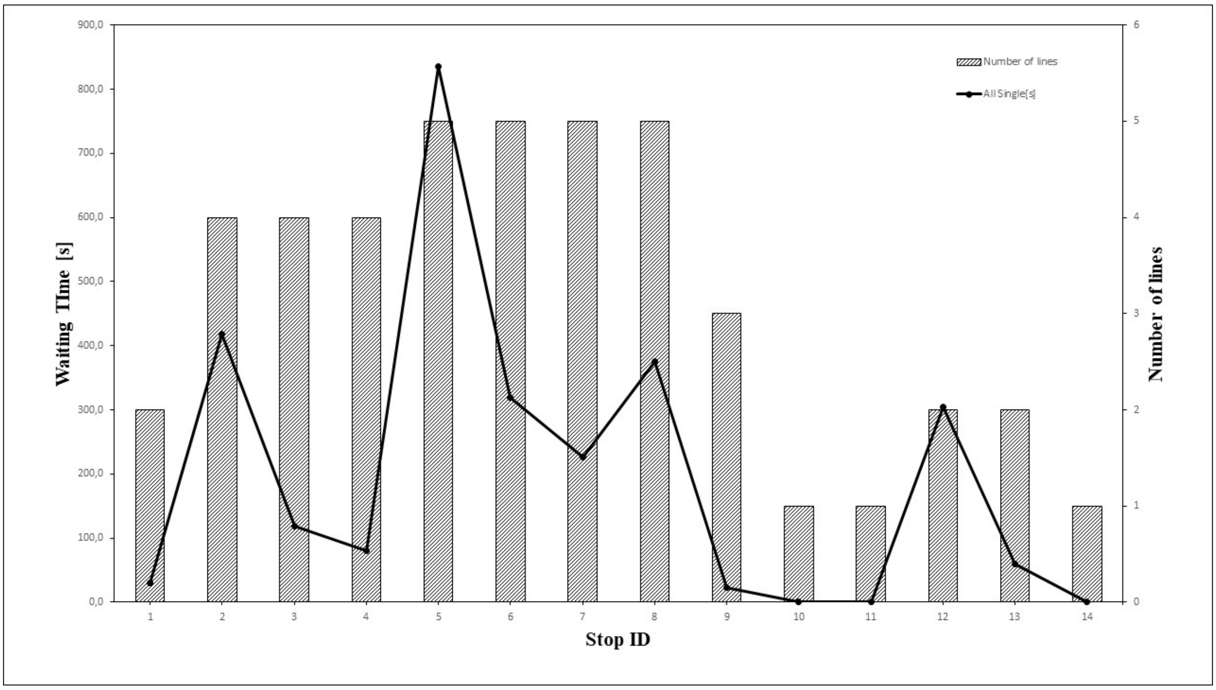

Fig. 5.8: Waiting Time's means for each stop for all stops single.

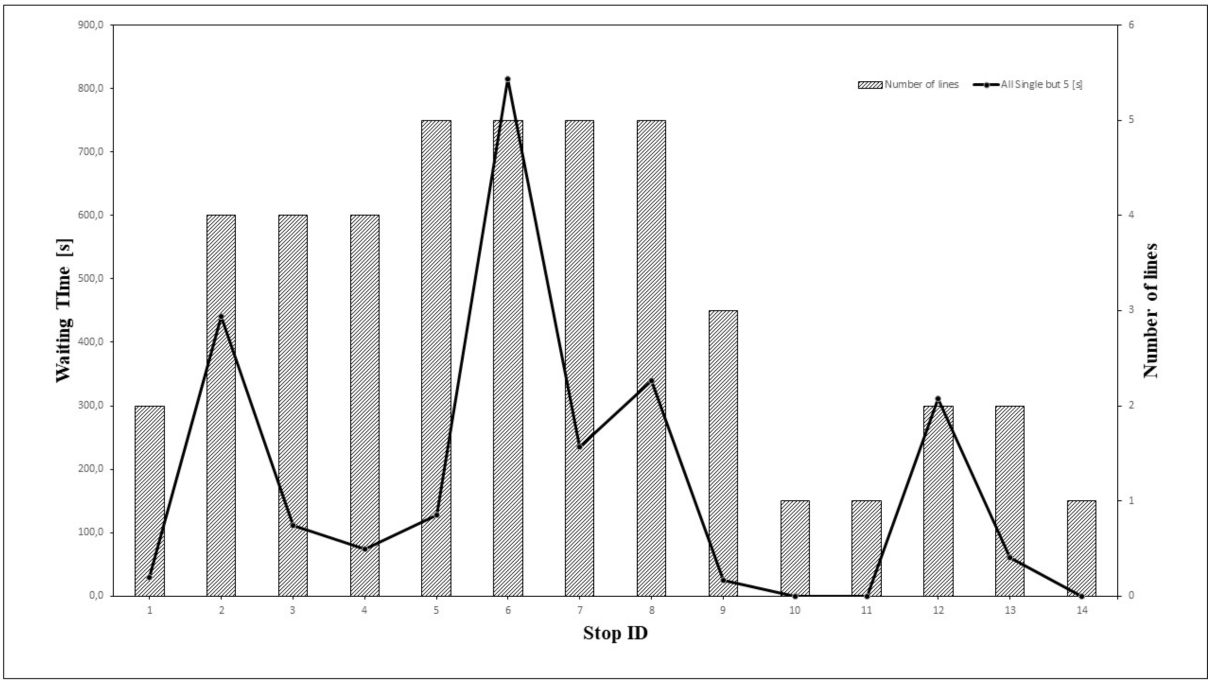

Fig. 5.9: Waiting Time's means for each stop for all stops single but 5.

occurs. While the other stops with five lines (stops 6, 7, and 8) do have considerable Waiting Times, they are nowhere near the magnitude of stop 5's Waiting Time.

When stop number 5 is converted from single to double, its Waiting Time decreases significantly. However, this reduction comes at the expense of the subsequent stop in the high load zone, which in this case is stop number 6. It appears that stop 5 was acting as a bottleneck, limiting the occurrence of Waiting Time in the other stops. By converting stop 5 to a double stop, it no longer acts as a processing interference and delivers vehicles with the same variability it receives, causing the next single stop (stop number 6) to become the new bottleneck.

Considering this, changing stop number 5 from single to double greatly helps in reducing the Waiting Time at that specific stop. However, the overall reduction in total Waiting Time is not as rapid because the change has caused the next stop (stop number 6) to become more vulnerable to Waiting Time, increasing its Waiting Time and offsetting some of the positive impact of the change.

This conclusion brings forth a significant revelation. Most of the literature reviewed so far has focused on analyzing and simulating individual stops in isolation. However, the latest finding highlights the fact that changes made to a particular stop can have consequences on other stops within the network. This suggests that improvements made to a specific stop may not necessarily translate into equivalent improvements for the entire tramway network system. Consequently, it becomes valuable to simulate subsets of the tramway network instead of treating stops as isolated entities.

Continuing the investigation on minimizing waiting time with minimal changes, the objective is to determine the optimal order in which stops should be converted from single to double stops. To address this question, it is assumed that all stops have the potential to cause traffic interferences, and thus, the waiting times at each stop are equally significant. It is important to note that this assumption may not reflect the actual case, as it is known that certain stops pose no risk of causing traffic disruptions due to the presence of a vehicle outside. If that was the case, these "no-matter-what" stops will be placed at the end of the sorted list of stops.

Four different methods have been considered for sorting the order in which stops will be converted from single to double:

- Random order. Although this may not appear to be the insightful method, it is interesting to explore whether there is any difference between using a more systematic sorting method or assigning the order randomly. This serves as a baseline to assess potential improvements.
- Sequential order. The stops will be converted in the order of their numerical sequence, starting from stop number 1 and progressing up to 14. While this may seem somewhat arbitrary due to the system's circular nature, it is worth investigating whether changing stops in the order they are encountered by the vehicles contributes to any improvement. This approach aims to create a "wave-like" effect of improvement.
- "Worsts First Static" (WFS) strategy: This approach aims to address the system's primary pain points by identifying the stop with the highest waiting time and selecting it for conversion first. To implement this strategy, the simulation will be initially run with all stops set as single stops. Subsequently, the stops will be sorted in descending order based on their waiting times. It is referred to as static because, despite running multiple simulations

due to the Central Limit Theorem (CLT), the stop sorting remains constant once the results are obtained.

- "Worst First Dynamic" (WFD) strategy: This approach involves incorporating more information but at a higher computational cost. Similar to the previous strategy, the stops will be sorted based on their waiting times after the first CLT simulation run. However, instead of determining the complete order of stops based on the initial CLT results, the simulation is rerun after each conversion to recalculate which stops are now the worst performers. This approach stems from the finding that the worst-performing might be a different one after changes are applied. It is referred to as dynamic because it incorporates new information from subsequent simulation runs before deciding which stop to convert next.

The results of these methods are presented in Table 5.10 and Figure 5.10.

Double Stops	**TWT Random [s]**	**TWT Sequential [s]**	**TWT Worst Static [s]**	**TWT Worst Dynamic [s]**
0	2755.84	2769.66	2784.67	2813.26
1	2773.52	2769.65	2711.43	2660.38
2	2712.95	2751.86	2564.81	2495.96
3	2808.29	2732.27	2277.59	2231.19
4	2763.82	2646.45	2224.70	1501.83
5	2765.81	2468.01	2031.61	1456.63
6	2611.12	2238.29	1396.15	1361.54
7	2486.66	1881.80	1353.62	933.34
8	2539.63	930.18	838.34	885.05
9	2533.15	781.08	605.77	571.47
10	2298.15	801.55	565.20	435.78
11	2339.03	782.76	446.69	438.24
12	1983.35	736.50	467.19	438.71
13	1436.64	436.99	431.60	429.75
14	442.45	435.18	452.58	437.85
Cumulative	**35250.41**	**25162.23**	**21151.95**	**19091.00**

Tab. 5.10: Total Waiting Time for different numbers of double stops following the four methodologies.

Analyzing the results from Figure 5.10, it is evident that the Random methodology performs the worst, showing minimal improvement in reducing Waiting Time at the beginning. On the other hand, the sequential order shows a significant improvement at the mid-section of the chart. The WFS methodology further improves upon the sequential order, indicating that using Waiting Time as a factor for decision-making leads to more substantial improvements initially. Lastly, the WFD methodology yields the best result, as running the simulation before each decision allows for smarter and more informed choices.

To quantify the rate of improvement, the area under each curve (cumulative waiting time) for each methodology can be calculated. A smaller area indicates a faster reduction of Total Waiting Time at each change, which signifies a more efficient methodology. The cumulative waiting time values for each methodology can be found in Table 5.10. Figure 5.11 presents a bar chart comparing the cumulative waiting time for each methodology, providing a visual representation

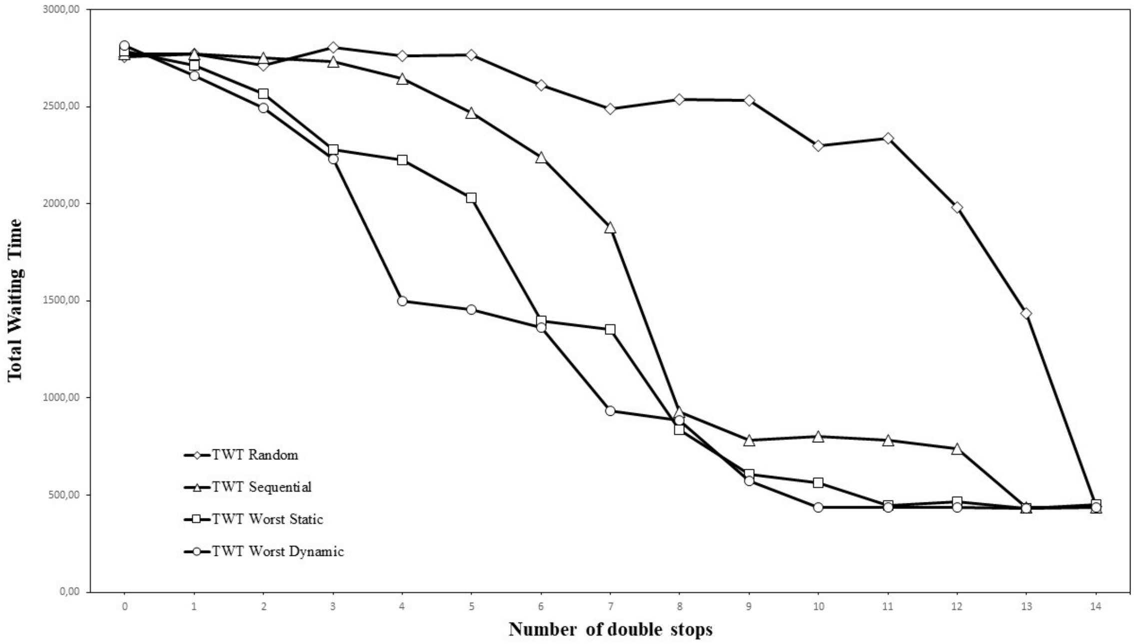

Fig. 5.10: Total Waiting Time progression for the four methodologies.

of their performance.

By examining Figure 5.11, it becomes clearer which methodologies yield the best and worst results in terms of minimizing Waiting Time.

Based on the results and the decisions made by the WFD methodology, that can bee seen with more detail in Table 5.11, it appears that the best criterion for improving Total Waiting Time is to prioritize changing stops that have a higher number of lines passing through them. The methodology follows a sequential order, starting with stops that have the most lines and gradually moving to stops with fewer lines. This approach is evident in Figure 5.10, where the Total Waiting Time decreases steadily until the last stop with the highest number of lines is changed, resulting in a significant reduction in Total Waiting Time. For instance, the initial four stops to undergo conversion are stops 5, 6, 7, and 8, each serving five lines. The Total Waiting Time experiences a decrease of approximately 200 seconds with each alteration, except for the final conversion, which results in a reduction of over 700 seconds.

Based on this observation, a general rule of thumb can be derived: to improve Total Waiting Time, prioritize changing stops from single to double based on the number of lines passing through them. Begin with stops that have the most lines, continuing in a sequential order if there are multiple stops with the same number of lines. Once all stops with the highest number of lines have been converted, proceed to the next group of stops according to the number of lines they have. Repeat this process until all stops have been changed to double stops.

It is important to note that this rule of thumb is based on the specific analysis and simulation conducted in this study. Other factors and considerations, such as the specific characteristics of the tramway network and the location of stops, should be taken into account for a comprehensive

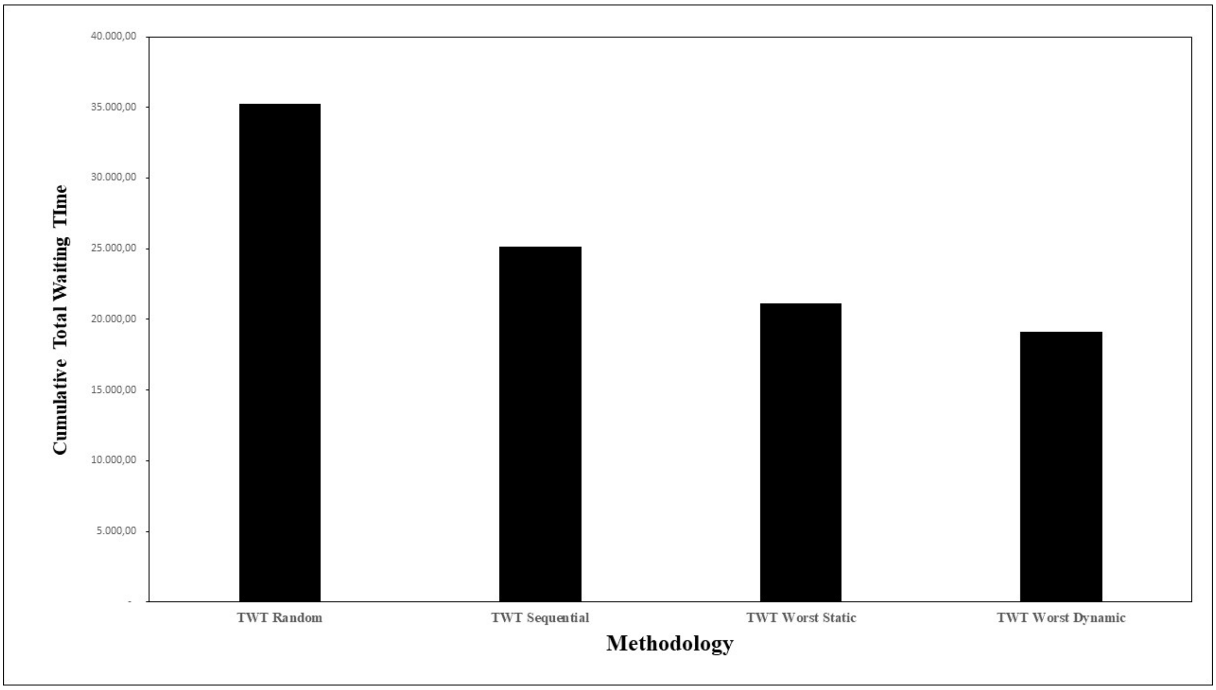

Fig. 5.11: Cumulative Total Waiting Time for the four methodologies.

analysis and decision-making process in real-world scenarios.

Double Stops	Number of lines	Changed Stop	TWT [s]
0	-	-	2813.26
1	5	5	2660.38
2	5	6	2495.96
3	5	7	2231.19
4	5	8	1501.83
5	4	2	1456.63
6	4	3	1361.54
7	4	4	933.34
8	2	12	885.05
9	2	13	571.47
10	3	9	435.78
11	2	1	438.24
12	1	10	438.71
13	1	11	429.75
14	1	14	437.85

Tab. 5.11: Detailed progression of Total Waiting Time for WFD methodology.

Similarly to the Analysis for the Average Period, the final experiment conducted regarding Waiting Time aims to analyze the behavior of the Total Waiting Time as the frequency of the lines approaches the saturation point. The Utilization Factor (ρ) is gradually increased from 0.3, closely resembling real conditions on the Vienna Ring, up to 2. This factor is calculated based on the Arrival Rates of stops with the highest number of lines, representing the worst-case scenario. The Total Waiting Time is calculated as the sum of waiting times at all stops in the system. The results are depicted in Figure 5.12.

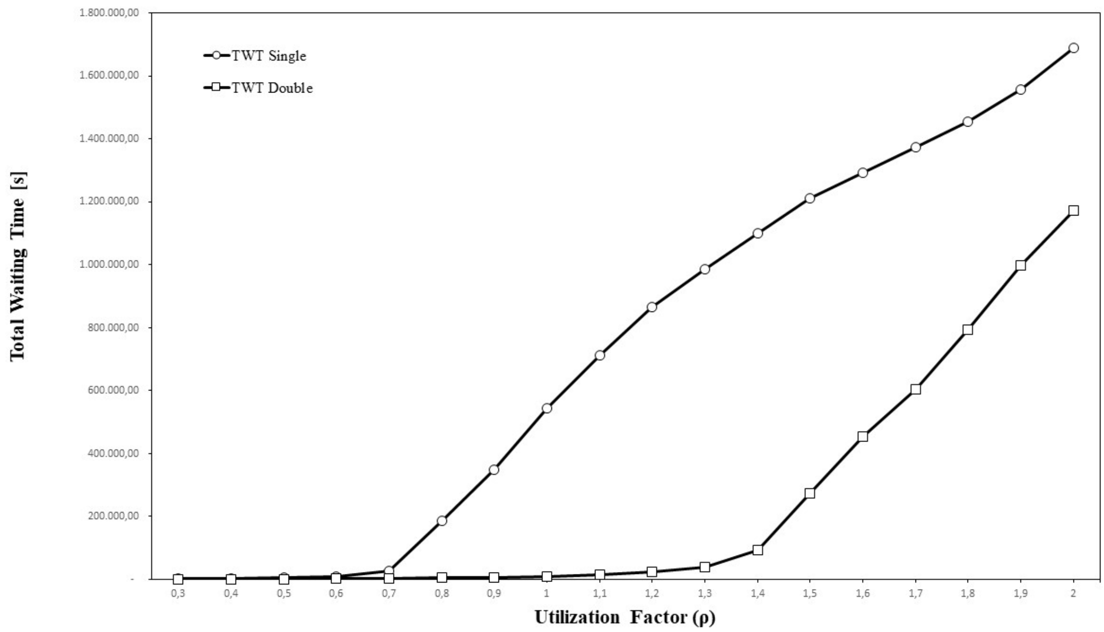

Fig. 5.12: Total Waiting Time progression for different Utilization Factors.

A similar pattern is observed for the Waiting Time. Both single and double stops exhibit a gradual increase in Total Waiting Time until reaching the Saturation Point. At this juncture, queues begin to grow indefinitely, resulting in a significant surge in the Total Waiting Time.

Chapter 6

Conclusions

6.1 Objectives Accomplishment

The primary focus of this thesis is to address the existing research gap and lack of literature regarding the implementation and quantification of the benefits of double stops within a tramway network. This research aims to achieve four specific objectives: (1) identify the key agents involved in defining a public transport tramway network and comprehend their interdependencies, (2) determine the primary performance parameters that accurately measure the efficiency and effectiveness of a tramway network, (3) design experiments utilizing a simulation framework to quantitatively evaluate the impact of double stops on these key performance parameters, and (4) develop a methodology that offers a comprehensive and adaptable approach for investigating and fulfilling research objectives in various tramway networks across different cities. The sequential nature of these objectives requires the successful accomplishment of each preceding objective to advance further, while the overarching fourth objective provides a general framework for the subsequent objectives.

The objectives outlined in this thesis have been successfully accomplished. Firstly, extensive literature review and comprehensive research have identified the agents that define the behavior and development of a tramway network, as well as how they interact with each other. The gathering and utilization of information regarding line frequencies, distances between stops, number of traffic lights, and dwell time for passenger alighting and boarding have been crucial in the development of a successful simulation tool. This tool not only incorporates the agents but also considers their implications and interactions. Accurate definition of different tramway network situations, such as vehicles blocking the entry or exit of stops, traffic light interruptions, and average tramway speed, has been employed. The collected and interconnected information has formed the basis of the simulation tool, which has subsequently been validated to confirm the relevance of the information used and the fidelity of the simulation.

Secondly, the two main parameters that measure the performance of the tramway network, namely the Average Period and the Waiting Time at each stop, have been identified. The Average Period, which is closely linked to stop capacity, allows us to determine if the tramway network is adhering to its scheduled time intervals based on line frequencies. Additionally, the Waiting Time is of significant importance, as deviations from the timetables, despite some waiting times being expected, can potentially cause traffic congestion due to vehicles waiting outside the stops.

Thirdly, different experiments have been designed to understand and quantify the implications of double stops. These experiments have explored various circumstances within the network, including all single stops, all double stops, and the actual real-world situation. Moreover, line frequencies have been adjusted to intentionally overload the stops and discover saturation points at each stop. The findings resulting from these experiments, which will be discussed in the findings section of this chapter, provide valuable insights into how changes in a specific stop can impact the performance of subsequent stops.

Lastly, both simulation tools and experiments have been designed to allow for user-defined inputs, enabling potential users to examine any subset of a tramway network of interest. This design allows for the exploration of various configurations and aspects of tramway networks, granting users the ability to conduct in-depth analyses.

In conclusion, all the objectives set forth in this thesis have been successfully accomplished. The research has contributed to a comprehensive understanding of the agents shaping tramway networks and their interactions, identified key performance parameters, explored the implications of double stops, and provided simulation and experimental tools for further investigations.

6.2 Key findings

This section presents a concise summary of the main findings and results obtained from the research, particularly the simulation experiments.

Double stops are not necessary in the Vienna Ring tramway network to maintain the desired Average Period at each stop. Regardless of whether all stops are single, all stops are double, or the stops have their real configuration, no significant changes in the Average Period were observed, as shown in Table 5.3.

Single stops reach their saturation point, where queues begin to grow indefinitely, at a Utilization Factor of 70%. However, for double stops, the saturation point occurs at a Utilization Factor of 140%, as depicted in Figure 5.6. This means that the Vienna tramway network can accommodate line frequencies approximately 2.13 times higher than the current frequencies using single stops. By incorporating double stops, this ratio increases to line frequencies 4.26 times higher than the existing ones.

The utilization of double stops significantly reduces Waiting Time in the Vienna Ring network compared to the scenario with all stops being single. The difference in Waiting Time between the best scenario (all stops double) and the worst scenario (all stops single) amounts to 2354 seconds over a three-hour simulation, as shown in Table 5.8

The simulation results shown in Figure 5.8 and 5.9 highlight the importance of considering subsets of stops rather than individual stops. Changes made to a single stop, such as converting it from single to double, may reduce Waiting Time at that specific stop but can result in increased Waiting Time at subsequent stops, leading to a less substantial overall reduction in Total Waiting Time.

The "Worst First Dynamic" (WFD) method, where the single stop with the highest Waiting Time is converted to a double stop, followed by rerunning the simulation, was identified as the most effective strategy for converting single stops to double. Although computationally costly, this approach yields the best results by achieving a faster reduction in Total Waiting Time with the fewest number of converted stops, depicted in Figure 5.11.

A derived rule of thumb suggests prioritizing the conversion of single stops to double based on the number of lines passing through them. Begin with stops serving the highest number of lines, progressing sequentially if multiple stops have the same number of lines. Once all stops with the highest number of lines have been converted, move on to the next group of stops according to their line count. Repeat this process until all stops have been converted to double stops.

Increasing line frequencies beyond the saturation points (0.7 for single stops and 1.4 for double stops) leads to a faster increase in Total Waiting Time. This acceleration occurs because queues begin to grow indefinitely, resulting in higher Waiting Time at each stop. Shown in Figure 5.12.

In conclusion, these findings shed light on the necessity and effectiveness of double stops in tramway networks, provide insights into the impacts of different strategies for converting single stops to double, and emphasize the importance of considering system-wide effects when analyzing tramway performance.

6.3 Significance and Implications

The significance and implications of the findings and methodology employed in this thesis encompass both research and practical perspectives.

From a research perspective, this study contributes to a better understanding of the double stop concept and its impact on Average Period and Waiting Time in a tramway network. The research highlights the factors influencing tramway performance and provides insights into the effectiveness of double stops in improving network efficiency. By investigating the behavior of tramway networks under different conditions and simulating various scenarios, this study enhances knowledge in the field and adds to the existing body of research on public transportation systems.

From a practical perspective, the developed simulation tool holds great practical value. It serves as a valuable instrument for analyzing existing tramway networks and designing new ones. Its flexible and adaptable nature allows users to input specific network configurations and experiment with different scenarios. Urban planners and transportation authorities can utilize this tool to evaluate the potential impact of implementing or removing double stops in a network. It provides a predictive capability to assess system performance and make informed decisions based on simulation results.

Furthermore, the simulation tool is particularly useful for exploring system behavior under special conditions. For example, it enables the examination of the network's response to temporary increases in line frequency due to unexpected events like traffic accidents or city-wide occasions requiring higher passenger flow. The versatility of the simulation tool, which has been developed using open-source Python code, empowers users to modify and customize the tool according to their specific requirements. This flexibility opens up a multitude of possibilities for further exploration and investigation in the realm of tramway networks.

6.4 Further research and development

Further research opportunities exist to enhance the accuracy and scope of the simulation tool by incorporating more valuable and specific data. The following areas could be improved by obtaining relevant data:

- Interdependencies between traffic lights. Currently, the simulation assumes that all traffic lights switch simultaneously from red to green and vice versa. However, it is known that traffic lights operate independently and may have different timings. Further research could explore the interdependencies between traffic lights in the studied tramway network to obtain more accurate results and reflect the real-world behavior of traffic signal systems.
- Alighting and boarding times. The simulation currently utilizes a normal distribution for dwell times based on data from a study conducted in another city [20]. While this has provided satisfactory results, incorporating data specific to the tramway network under investigation would be valuable. Different stops may have varying dwell times due to factors such as their design, passenger flow, or whether they are single or double stops. Collecting data on these cases and integrating it into the simulation would improve its accuracy and realism.
- Tramway speed variations. Currently, the simulation considers a single average speed for the tramways. However, it would be worthwhile to investigate whether tramways exhibit different velocities depending on the network section or other factors. Gathering data on tramway speeds in various sections and incorporating this information into the simulation would provide a more comprehensive representation of tramway operations.

By addressing these aspects and incorporating more precise data into the simulation, the accuracy and applicability of the tool can be further improved. This would enhance the understanding of tramway network performance and contribute to better decision-making processes for urban planners and transportation authorities.

6.5 Closing Statement

In conclusion, this thesis has successfully addressed the gap in research and literature concerning the implementation of double stops and their impact on tramway network performance. Through extensive research, simulation experiments, and analysis, several key findings have been obtained, shedding light on the behavior of tramway networks and providing valuable insights for urban planners and transportation authorities.

The research has demonstrated that, in the case of the Vienna Ring tramway network, double stops are not necessary to maintain the desired Average Period at each stop. Moreover, it has been discovered that single stops reach their saturation point at a Utilization Factor of 70%, while double stops can handle line frequencies up to 140% Utilization Factor. Additionally, the analysis of Waiting Time has revealed that double stops play a crucial role in reducing waiting times, leading to a substantial improvement in the overall performance of the network. Simulation results have shown that converting single stops to double stops based on the number of lines passing through them, following the "Worst First Dynamic" method, yields the best results in terms of reducing Total Waiting Time.

From a practical standpoint, the developed simulation tool provides a valuable resource for analyzing existing tramway networks and designing new ones. Its adaptable nature and open-source code enable users to tailor the tool to their specific needs and explore various scenarios. This tool serves as a decision-support system for urban planners, allowing them to assess the potential impact of implementing or removing double stops and predict the performance of the tramway system under different conditions.

In summary, this thesis contributes to the field of transportation research by offering valuable insights into the implementation and impact of double stops in tramway networks. The findings have practical implications for optimizing tramway operations and improving overall network efficiency. Further research opportunities exist to refine the simulation tool by incorporating more accurate data and exploring additional factors that influence tramway performance.

This study serves as a foundation for future investigations, providing a comprehensive understanding of double stops and their role in tramway network design and operation. By continuing to explore and refine these concepts, we can further enhance public transportation systems, contributing to sustainable urban development and providing efficient and reliable mobility solutions for communities.

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