TRANSIT SIGNAL PRIORITY ON EVROPSKÁ STREET IN PRAGUE

TOMÁŠ MÍČA

Master's Program in Engineering

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TRANSIT SIGNAL PRIORITY ON EVROPSKÁ STREET IN PRAGUE

by

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GRADUATE PROJECT

Presented to the Faculty of the Graduate School of

The University of Texas at El Paso

in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE

Department of Engineering Education and Leadership

THE UNIVERSITY OF TEXAS AT EL PASO

May 2023

Acknowledgements

First of all, I would like to thank my supervisors Dr. Ruey Long Cheu, The University of Texas at El Paso, and Dr. Tomáš Horák, Czech Technical University in Prague, for providing me valuable advice while writing this thesis and for the overall support throughout the studies at CTU and UTEP.

Secondly, I would like to thank Mr. Roman Dostál, for consultations and providing me with data needed for elaborating the experimental part of this thesis.

Finally, I would like to thank my family and friends for their encouragement and love throughout my studies and during trying times that I went through.

Declaration

This thesis/report is an output of the International Dual Master's Degree Program in Smart Cities Science and Engineering, a collaboration between Czech Technical University, Czech Republic, and The University of Texas at El Paso, USA.

This research is jointly supervised by the following faculty members:

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MASTER'S THESIS ASSIGNMENT

(PROJECT, WORK OF ART)

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Study programme (field/specialization) of the student:

master's degree – SC – Smart Cities

Theme title (in Czech): **Preference veřejné dopravy na Evropské třídě v Praze**

Theme title (in English): **Transit Signal Priority on Evropská Street in Prague**

Guidelines for elaboration

During the elaboration of the master's thesis follow the outline below:

- Analyze the current traffic loads on Evropská street
- Perform literature review on transit signal priority (TSP) systems
- Propose a new approach to public transit priority on Evropská Street
- Design and run a microsimulation model of Evropská street with proposed transit signal priority system
- Evaluate the results from the model and compare them with the model without TSP

Graphical work range: N/A

Accompanying report length: At least 55 pages.

Bibliography:

Smith H. R., Hemily B., Ivanovic M., Fleming G., Inc.: Transit Signal Priority (TSP): A Planning and Implementation Handbook. USDOT. 2005

Anderson P., Walk J. M., Simek CH.: Transit Signal Priority: Current State of the Practice. TCRP. 2020

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Ruey Long Cheu, Ph.D.

Date of master's thesis assignment: **June 30, 2021**

(date of the first assignment of this work, that has be minimum of 10 months before the deadline of the theses submission based on the standard duration of the study)

Date of master's thesis submission: **May 15, 2023**

a) date of first anticipated submission of the thesis based on the standard study duration and the recommended study time schedule
b) in case of postponing the submission of the thesis, next submission date results from the recommended time schedule

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I confirm assumption of master's thesis assignment.

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Prague .... December 12, 2022

Abstract

This diploma thesis deals with the topic of Transit Signal Priority (TSP). This traffic control strategy has been recognized as an important tool for improving the quality of service provided by public transit systems, reducing delays and stops, operating costs for transit operators, and even improving air quality. The objective of this thesis is to describe and evaluate the existing TSP system on Evropská Street in Prague and to propose possible improvements to this system. This includes the development of VISSIM microsimulation models of the 3.5 km long section of Evropská Street between Nádraží Veleslavín and the Prague Outer Ring Road. Four initial simulation models were created in the first phase, taking into account the current infrastructure and traffic volumes, as well as the planned tramway extension and forecasted volumes. The first two models with/without a tramway extension incorporate the 2022 volumes. The other two models are based on volumes forecasted for 2030 with/without the completed Ring Road. Based on the initial models' outputs, improvements to the TSP system were suggested in three scenarios, which were tested and evaluated within 2022 as well as 2030 volumes. The travel times of all modes of transport were compared across all the models, and possible travel time savings were calculated. According to the findings, recommendations on which TSP measures should be applied on Evropská Street were given.

Keywords: transit signal priority, public transit, Prague, Evropská Street, microscopic traffic simulation, PTV VISSIM

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Chapter 1: INTRODUCTION

1.1 Background

Transit Signal Priority (TSP) is a traffic management strategy that aims to improve the efficiency and reliability of transit services by giving priority to buses and other transit vehicles at traffic signals. TSP has been recognized as an important tool for improving the quality of service provided by public transit systems, reducing delays and stops, reducing operating costs for transit agencies, and even improving air quality. With growing urbanization and the increasing demand for sustainable transportation options, TSP has become an integral part of traffic control systems in many cities around the world, including Prague.

Despite the many benefits of TSP, there are still challenges that need to be addressed in its implementation. One of the key challenges is the need for finding a reasonable compromise between giving priority for public transit and sustaining a smooth flow of overall traffic. For this purpose, the potential impact of TSP on all modes of transportation must be properly examined before the TSP is implemented.

Additionally, close coordination and communication between transit agencies and traffic management authorities is required. Effective communication and collaboration are essential to ensure that TSP is implemented in a way that is consistent with the overall traffic management objectives of the city. Important factor to consider when implementing TSP is also the cost of planned measure. Specialized equipment and software for TSP can be expensive and the process of implementation time-consuming. In addition, TSP may require changes to traffic signal timing and phasing, which can be difficult to implement in some locations [1].

1.2 Research Objectives

This thesis examines the current state and potential of TSP implementations on Evropská Street in Prague, including its benefits, challenges, and impact on overall traffic flow in the area. For this purpose, a microscopic traffic simulation model of the western section of Evropská Street is created in VISSIM. Based on the model outputs, various new scenarios for TSP in the area are explored and evaluated in order to provide recommendations for improving the effectiveness and efficiency of public transit. This thesis contributes to the ongoing discourse on the role of TSP in promoting sustainable transportation options and improving the overall quality of Prague's transportation system.

1.3 Thesis Outline

Chapter 1 is the introduction to the system of transit signal priority and provides description of the thesis objectives and thesis outline.

Chapter 2 focuses on the detailed description of transit signal priority strategies, its benefits and drawbacks and then specifically focuses on TSP implementations in Prague.

Chapter 3 provides the review of the research area and the detailed description of the traffic in the area. This chapter includes a summary of the public transit services provided in the area and the signal traffic control on Evropská Street.

Chapter 4 describes the software tool used for the microscopic traffic simulation and explains the model design together with description of data used as simulation inputs.

Chapter 5 analyzes outcomes obtained from the initial simulation models and based on that suggests improvements to the existing TSP system.

Chapter 6 contains experiments with TSP demonstrated in the research area. Results from all suggested scenarios are then compared and evaluated.

Chapter 7 gives the conclusion of the research presented in this thesis together with the summary of the results. Moreover, it provides recommendations for possible TSP improvements on Evropská Street based on the simulation outputs. Suggestions for possible future research are covered at the end of the thesis.

Chapter 2: REVIEW OF TRANSIT SIGNAL PRIORITY

Transit Signal Priority (TSP) is a set of tools implemented into signal controllers at intersections to enable public transit vehicles to go through the intersection without stopping or with the shortest stop possible. The TSP measures include extending the green lights, shortening red lights, rotating of phases, etc. The overall goal is to make transit service more reliable, faster, and more cost effective [1]. TSP can be used in the operations of buses, trams, or light rail lines, especially at the intersections where transit vehicles mix with or have conflicts with the general vehicular traffic.

2.1 Terminologies

Active versus passive TSP

Generally, we can classify the transit signal priority techniques as passive or active. Passive TSP techniques typically only involve optimizing fixed signal programs or coordinating successive signals to create a "green wave" for traffic along the transit line's route, the active TSP relies on specialized hardware (such as radio communication and specialized traffic signal controllers) to detect transit vehicles approaching the intersection and adjust the signal timing dynamically to improve service for the transit vehicles.

Absolute versus conditional TSP

According to the level of priority given to transit vehicles, a TSP may be conditional and absolute. The conditional priority is used at intersections with complicated traffic conditions, where multiple transit routes clash or have a major conflict with other traffic flow. At intersections with simple traffic movements, an unconditional (absolute) transit priority can be implemented. Setting rules for signal priority depends on the goals of the TSP system agreed to by both the transit agency and the signal operations agency. At intersections or sections with heavy volumes in conflicting movements, a system without any TSP is recommended [2].

Passive versus active detection

Detection allows to determine the location of the transit vehicle at the intersection and sends this information to the signal controller for further evaluation. There are various types of detectors (trolley links, GPS, video detection, radio detection, inductive loops, etc.) that can be used. Detection of transit vehicles can be either passive or active. Passive detection is when a vehicle drives over / touches a detector and is only used at places that are specifically dedicated for transit (tram tracks). Active detection is more advanced system based on contactless communication via radio, radio, or GPS.

2.2 Active TSP

Active transit signal priority gives priority to public transit vehicles at intersections by adjusting the traffic signal timings in real-time. The system uses sensors and communication technologies to detect approaching transit vehicles and adjusts the signal timings to give priority to the transit vehicles.

A necessary condition for active TSP is a dynamic signal control system that allows the controller to modify the signal plan in real time or create a new timing plan according to current traffic demands detected by traffic detectors. The adjustments to the signal plan may include changes to the length of green signals and alternating the control phases according to actual demand.

Active TSP systems require four components: a detection system aboard transit vehicles; a priority request generator (transmitter) which can be aboard the vehicle or at a centralized management location; a strategy for prioritizing requests; and an overall TSP management system (software) [3].

Bus priority

Bus priority mostly uses active detection. It is based on transmitting of radio telegram from the approaching bus to the signal lights controller (communication starts several hundred meters before the intersection). The radio telegram transmitted from the vehicle contains information about the direction of travel of the bus at the intersection and also the information about whether the bus is delayed. Given this information, the signal controller can react in advance and adequately adjust the timing plan.

Tramway priority

When a tram needs time to pass through the intersection, a preferential intervention to the traffic signal plan will take place based on the tram's request. There are many examples of how the controller gives priority to trams, and each controller works on the basis of its own control logic, which is different for each intersection.

For a tram passing through a signalized intersection with two detectors (check-in and check-out detectors) the intervention to the signal plan looks as follows [2]:

1. When the tram passes the check-in point (250-500m before the stop line), its movement is recorded by the detector.

2. The controller receives information from the check-in detector about the arriving tram. It knows the time needed for the tram to arrive and pass through the intersection (apx. 30s).

3. Based on the control logic and entered data, the controller evaluates the situation. If it finds that without intervention to the signal plan, the tram will not pass through the intersection, it will implement one of the following measures or a combination of them: extension of some phase, shortening some phase, changing the order of phases, inserting an extra phase.

4. When tram passes the check-out point; this fact will be recorded by the detector.

5. The controller accommodates the demands of other users of this intersection.

2.3 Passive TSP

Unlike active transit signal priority, which requires the vehicle to send a request to the traffic signal controller to ask for priority, passive TSP automatically gives priority to transit vehicles based on their pre-determined schedule.

One of the key advantages of passive TSP is that it does not require any additional infrastructure or communication equipment. This means that it can be easily implemented in the existing traffic signal systems. However, if the transit vehicles are not operating on a fixed schedule or if they are running behind schedule, the passive TSP system may not be as effective in providing priority.

Apart from giving priority through signal phasing, some other measures of passive TSP exist.

Dedicated transit lanes

In this system, a dedicated lane is provided for transit vehicles, which helps them to bypass traffic congestion and travel more quickly. The lanes are usually marked with special road markings or signage to differentiate them from regular lanes. Besides the operation of transit, some other vehicles such as taxis, motorcycles, cyclists, and emergency vehicles are also often permitted to use these lanes.

Figure 1: Dedicated bus lane on Evropská Street in Prague. [Google Maps]

Queue jump lanes

These are lanes that allow transit vehicles to bypass a queue of cars waiting at a stop line during the red signal. This is achieved by providing a separate lane or a short segment of road where the bus can move ahead of other vehicles and get to the front of the queue. A queue jump lane is usually accompanied by a signal which provides a phase specifically for transit vehicles within the queue jump. The transit vehicles in the queue jump lane get a "head-start" over other queued vehicles and can therefore merge into the regular travel lanes immediately downstream of signal. This solution is often found in bus rapid transit systems [4].

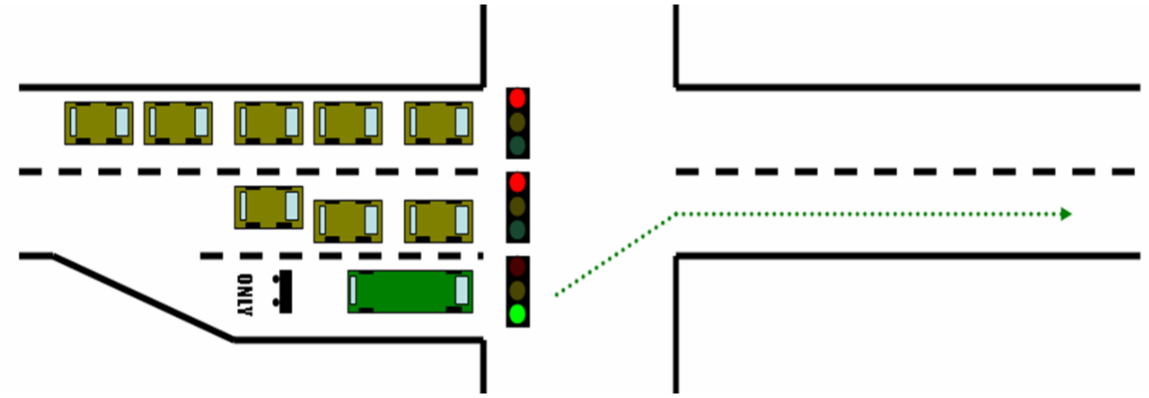

Figure 2: Queue jump lane with a designated signal. [Wikipedia.org]

Operation of buses on tram track

The advantage of operating buses on the tram track is that buses get their exclusive right-of-way with minimal expenses and at the same time the number of lanes for general traffic is preserved. There is also an opportunity of building joined stops for both tramways and buses, which creates attractive transfer points for passengers.

The operation of buses on a tram track has its own specific operational aspects. A dedicated bus lane on a tram track can be reserved exclusively only for buses and cannot be reserved for other types of vehicles (e.g., coaches, bicycles, taxi vehicles). Drivers of buses traveling on the tram track follow exclusively the signals for trams at intersections.

2.4 TSP applications

Transit signal priority (TSP) has been implemented in various cities worldwide. Bellow you find some examples of cities that have implemented TSP and the description of its benefits.

Los Angeles, USA: Seattle implemented TSP in the early 2000s to improve bus travel times and reliability. The program was successful in reducing bus wait times at traffic signals and improving bus speeds. Total transit time savings were reduced by 25 percent and delays caused by traffic signals were reduced by 33 percent [5].

London, UK: TSP has been used on London's buses and trams, resulting in reduced travel times and increased passenger satisfaction. According to Transport for London, TSP has helped to reduce journey times by up to 10% on some routes [6].

Sydney, Australia: The Sydney Bus Priority Program has implemented TSP at over 600 intersections, resulting in improved bus reliability and reduced travel times. A study published in the Journal of Public Transportation in 2013 found that TSP implementation in Sydney resulted in an average reduction of 14 seconds in delay per bus trip [7].

In many cases, TSP has also helped to reduce congestion and improve traffic flow, benefitting all road users.

According to National Association of City Transportation Officials, active TSP can reduce transit delay significantly. In some cases, bus travel times have been reduced around 10%, and delay was reduced up to 50% at target intersections [8]. The U.S. Federal Transit Administration (FTA) recognizes the significance of TSP in the successful implementation of Bus Rapid Transit systems. In a demonstration project carried out on crowded bus lines in Los Angeles County Metro, TSP was shown to enhance travel time savings by 25% and, on one route, boosted overall travel speeds by 29% [5].

TSP is effective at intersections with routinely long queues, or on commonly delayed transit routes. TSP is most effective at intersections with a far-side stop or no stop, allowing the bus to clear the intersection without waiting for a signal [1].

2.5 TSP evaluation

It is crucial for transit operators to be able to fairly compare the various types of TSP technologies. The report "Transit Signal Priority Research Tools" published by FTA provides a set of Methods of Evaluation (MoEs) for this purpose. The three crucial aspects to assess are the proper functioning of the technology, improvement in transit system performance in terms of time savings and reliability, and the impact of TSP technologies on other roadway users [9].

Evaluating the TSP can be done using several methods. Bellow you find a summary of these methods.

Travel time analysis: This involves comparing the travel time of transit vehicles before and after the implementation of TSP. The reduction in travel time can indicate the effectiveness of the priority system.

Passenger wait time: This involves measuring the wait time of passengers at transit stops before and after the implementation of transit signal priority. A reduction in wait time can indicate an improvement in transit service.

On-time performance: This involves measuring the percentage of transit vehicles that arrive at stops on time before and after the implementation of transit signal priority. An increase in on-time performance can indicate that the priority system is improving schedule adherence.

Passenger satisfaction: This involves surveying passengers before and after the implementation of TSP to assess their level of satisfaction with the transit service. An increase in passenger satisfaction can indicate that the priority system is improving the overall transit experience.

Vehicle delay analysis: This involves analyzing the causes of transit vehicle delays before and after the implementation of transit signal priority. A reduction in delays can indicate that the priority system is improving transit reliability.

Mode share analysis: This involves comparing the mode share of transit before and after the implementation of TSP. An increase in the mode share of transit can indicate that the priority system is making transit more attractive to riders.

These measures can be used individually or in combination to provide a comprehensive evaluation of the TSP system. The specific methods used will depend on the goals of the evaluation and the data available.

2.6 TSP costs

The costs of TSP can vary depending on the type of technology used, the size of the system, and the level of implementation. The cost of hardware and software components, such as traffic controllers and on-board equipment, can be substantial, but this cost is usually offset by the benefits of improved transit performance and reliability. Other costs associated with TSP implementation may include:

1. Studies and analyses to determine the feasibility of the TSP system and to identify the most effective technology for the specific transit network.

2. Installation and implementation of the TSP system, which may involve installing new hardware and software components, reconfiguring existing traffic signals, and modifying transit vehicles.

3. Training and support services to ensure that the TSP system is used effectively and efficiently by transit operators and other road users.

4. Maintenance and upkeep of the TSP system, including regular software updates and replacement of hardware components.

5. Disruption costs: This includes the cost of any disruption to traffic flow during the implementation of TSP, such as lane closures or detours.

In general, the cost of TSP systems can be offset by the benefits they provide, such as improved transit travel times and reliability, increased passenger satisfaction, and reduced emissions and fuel consumption [1]. The specific costs associated with TSP implementation will depend on the specific requirements of each transit system, and it is important for transit operators to carefully consider these costs when deciding whether to implement a TSP system.

2.7 Transit Signal Priority in Prague

Prague's transport operator DPP (Dopravní podnik hlavního města Prahy), which is responsible for operating subway, trams, and buses in Prague, has been adopting TSP solutions for trams since late 1980s. A big progress in traffic signal control came after introduction of microprocessor controllers in the 1990s. In 1996, the municipal council approved the document of "Principles of transport policy of Prague", which supported the implementation of TSP as well as physical priority measures (such as dedicated bus lanes, semi-reserved tram tracks). Some of the principles of transit priority are also enforced by law (prohibition of cars driving on the tram track, dedicated lanes for buses). The legislative framework is also made up of decrees (No. 294/2015), technical standards and conditions for construction and transport solutions, the Transport Policy of Prague from 2017 and other strategic documents [10].

In 2017, a new strategic document called „Project of TSP in Prague in 2016-2020" was presented. The document defines the strategic and organizational framework for the application and implementation of transit priority measures, summarizes the current development of TSP solutions in Prague and, above all, lists problem locations for tram and bus priority.

As in February 2023, TSP has been implemented at 231 out of 253 tramway intersections in Prague (91.3%). The ratio of the conditional and absolute TSP is 72:28 and strictly passive detection is used. At the remaining intersections, the TSP is not implemented mostly due to outdated control software and/or missing detectors. At intersections located at crossings with Magistrála (the busiest road in the centre of Prague), the traffic conditions do not allow the implementation of TSP [9]. See the Figure 3 with all tramway intersections in Prague.

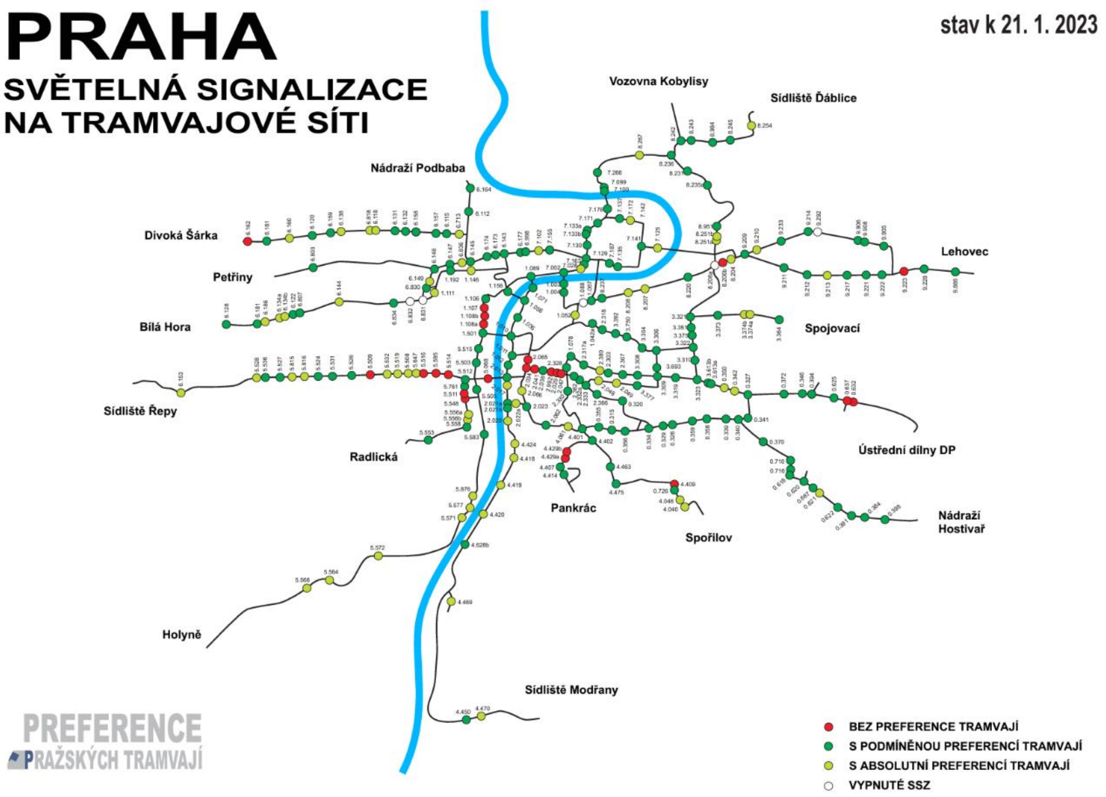

Figure 3: The map of tramway intersections in Prague. RED = without TSP, DARK GREEN = conditional TSP, LIGHT GREEN = absolute TSP. [Pražské tramvaje]

The Prague’s transport agency statistics showed that at intersections with absolute TSP, the average delay of trams dropped by 85-95% after TSP implementation. At the intersection with conditional TSP, the average delay dropped by 30-90%, depending on the complexity of traffic solution [11].

Prague’s tramway priority system has been for years more advanced system than bus priority, but traffic signal controllers with active detection of buses has recently been implemented at many new or reconstructed signalized intersections and all buses of Prague’s transit operator DPP are now equipped with technology for active detection. As of 2022, there were 526 signalized intersections with bus routes and at 265 (50.4%) of them was implemented TSP (255 with active detection and 10 with passive detection). The development of active detection systems can be therefore a promising factor for greater expansion of TSP in the future [12].

Passive TSP in Prague

Apart from active TSP, some other measures for prioritizing public transit have been implemented in Prague. These measures aim to segregate operation of public transit vehicles from general traffic by creating dedicated bus lanes or allowing operation of buses on tram track. The total length of dedicated bus lanes in Prague in 2021 was 62 km, 45 km of these lanes were applied on travel lanes and 17 km on tram track [13]. Some intersections in Prague have been also redesigned to allow public transit vehicles to bypass the regular flow of traffic, further reducing wait times. In the case of trams, the physical segregation from other traffic is achieved by constructing tracks on separate strips, or by separating them by concrete curbs.

Figure 4: Stop with joined operation of trams and buses in Prague. [preferenceVHD.info]

Chapter 3: TRAFFIC ON EVROPSKÁ STREET

3.1 Location

The Evropská Street is one of the major roads in Prague. Located in Prague district 6, on the west bank of the Vltava River, it connects the Vítězné náměstí in Dejvice in the broader city center with the north-western suburbs. The corridor ends at the intersection with Prague Outer Ring Road (Pražský okruh – D0), just 2.5 km away from the Václav Havel Airport Prague. The path of the street reaches cadastral areas of Dejvice, Veleslavín, Vokovice, Liboc, and Ruzyně. The location of Evropská Street is displayed on the map in Figure 5.

The street is known for its modern architecture, as well as its numerous commercial and office buildings, shopping centers and luxury apartments. It is also a popular destination for locals and tourists thanks to its location near the airport, easy access to public transportation, and proximity to several notable attractions such as the Šárka Valley Park. Additionally, the street is a hub for business and commerce, with several multinational companies having their headquarters or branches along Evropská třída.

The total length of this east-to-west oriented road exceeds 7 km, with most of the route being a 4-lane divided highway. On the first 5 km westbound from the Vítězné náměstí, there is a separate tramway track in the median. Along the whole route there are 14 signalized intersections, 8 signalized pedestrian crossings and 11 tram stops. Below the surface of the first 3.5 km of the street, is a part of the subway line A with 3 stations: Dejvická, Bořislavka and Nádraží Veleslavín. The latter is a major transfer point between subway, city buses, regional buses and trains. The most important bus connection with the Prague's Airport departures from this terminal.

Figure 5: Map of Evropská Street. [Mapy.cz]

3.2 Traffic flows on Evropská Street

Evropská Street is one of the top 10 busiest roads in Prague (excluding the Outer and Inner Ring Road). The average daily traffic (ADT) flow in both directions in 2021 was estimated to be 41,100 vehicles / day on the busiest section of the street (Na Pískách – Horoměřická). In the western section between Libocká and Drnovská Street, the average traffic flow was 31,800 veh/day. The section between Nádraží Veleslavín and Divoká Šárka has an average flow of 33,400 cars/day, 1400 slow vehicles/day (trucks, coaches), 586 buses/day and 412 trams/day. This data comes from annual statistics of Technická správa komunikací (TSK), the city-owned company responsible for road maintenance and traffic surveys [13].

Evropská Street is, for most of its length, a 4-lane divided road (2 lanes in each direction), except the sections in eastbound lanes with a right lane dedicated for buses, taxis, emergency vehicles and cyclists. This dedicated lane consists of 5 separated sections (73a, b, c, d, e), with the first section starting in the very west part of the Street and the last section ending close to the Veleslavín transfer center (only in this direction). This infrastructure measure was implemented here mainly to give priority to buses, which were often stuck in traffic and thus were delayed. The dedicated bus lane is enforced only on working days (Monday to Friday) from 6:00 a.m. till 8:00 p.m. Outside these hours, it is available for all traffic.

The speed limit on most of the route of Evropská Street is 60 km/h. At some sections near intersections the maximum speed is restricted to 50 km/h. On the very west section of Evropská Street (1.5 km) the drivers can speed up to 70 km/h. The travel time from one end to other end of Evropská Street can take 7-10 minutes (during low volumes at night), up to 13-16 minutes (in the evening peak) according to Google Maps [14].

There are 7 signalized intersections (5 of them involving trams) and 3 signalized pedestrian crossings in the research area. All these intersections have dynamic signal control, which means that their signal plans are dynamically changing according to real-time traffic conditions. The controller processes the demands from vehicle, bicycle and pedestrians' detectors as well as the requests for TSP. Figure 6 shows the location of all signalized intersections in the area and Table 1 lists the description of their signal control, including a level of transit signal priority.

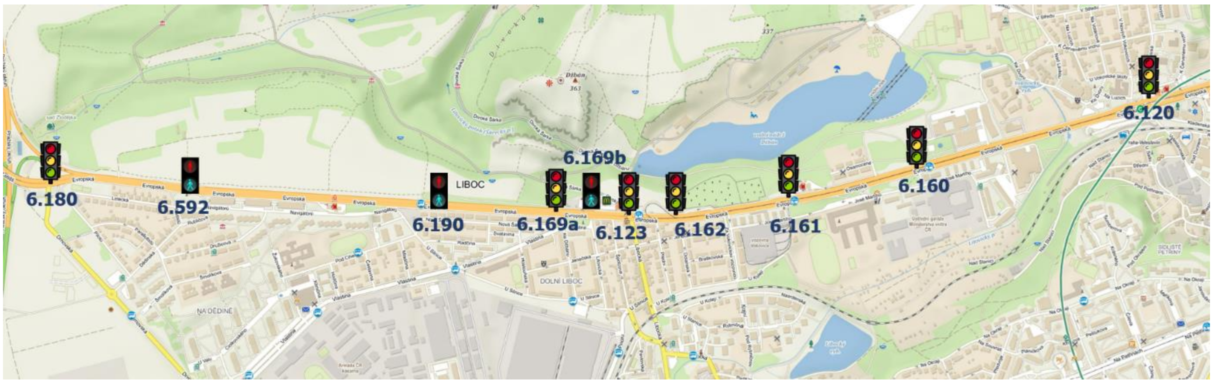

Figure 6: Location of signalized intersections in the research area. [Mapy.cz]

Table 1: List of signalized intersections on Evropská Street.

Nr.	Sign	Location	Signal Control System	Transit Signal Priority	
				BUS	TRAM
1	6.120	Evr. at Veleslavínská	dynamic	no	yes (conditional)
2	6.160	Evr. at garáže MV	dynamic	yes (active)	yes (absolute)
3	6.161	Evr. at Do Vozovny	dynamic	no	yes (conditional)
4	6.162	Evr. at Divoká Šárka loop	dynamic	no	no
5	6.123	Evr. at Libocká	dynamic	no	–
6	6.169b	Evr. at pedestrian crossing	dynamic	no	–
7	6.169a	Evr. at Vlastina	dynamic	no	–
8	6.190	Evr. at pedestrian crossing	dynamic	no	–
9	6.592	Evr. at pedestrian crossing	dynamic	yes (passive)	–
10	6.180	Evr. at Drnovská	dynamic	no	–

It is to be noted that the TSP on Evropská Street is currently only implemented for trams. Buses operated by Dopravní podnik hl. města Prahy (routes within the city) are equipped with the technology needed for communication with signal controllers at intersections (the technology is owned by DPP) but do not have priority, because the signal controllers at most of the intersections on Evropská Street can only receive calls from passive detection (trams), and do not support active detection of buses. Regional buses are operated by private transit operators, who do not own the TSP technology for active detection provided by DPP, and therefore could not be detected. The west part of Evropská Street is due to this reason marked as a "problematic" area in terms of transit priority on the official website of Prague's Integrated Transport [15]. Figure 7 shows the scheme of all tramway intersections on Evropská Street and their level of TSP.

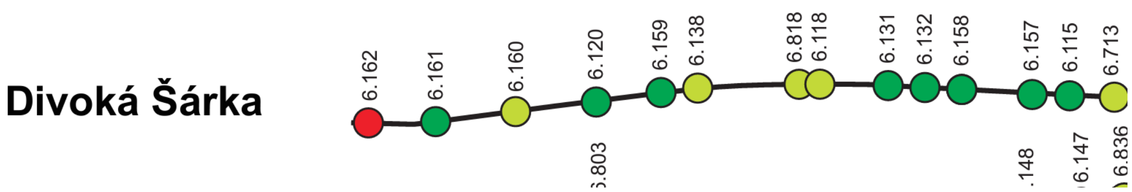

Figure 7: Tramway signal priority on Evropská street. RED = no TSP, DARK GREEN = conditional TSP, LIGHT GREEN = absolute TSP. [Pražské tramvaje.cz]

3.3 Public Transit

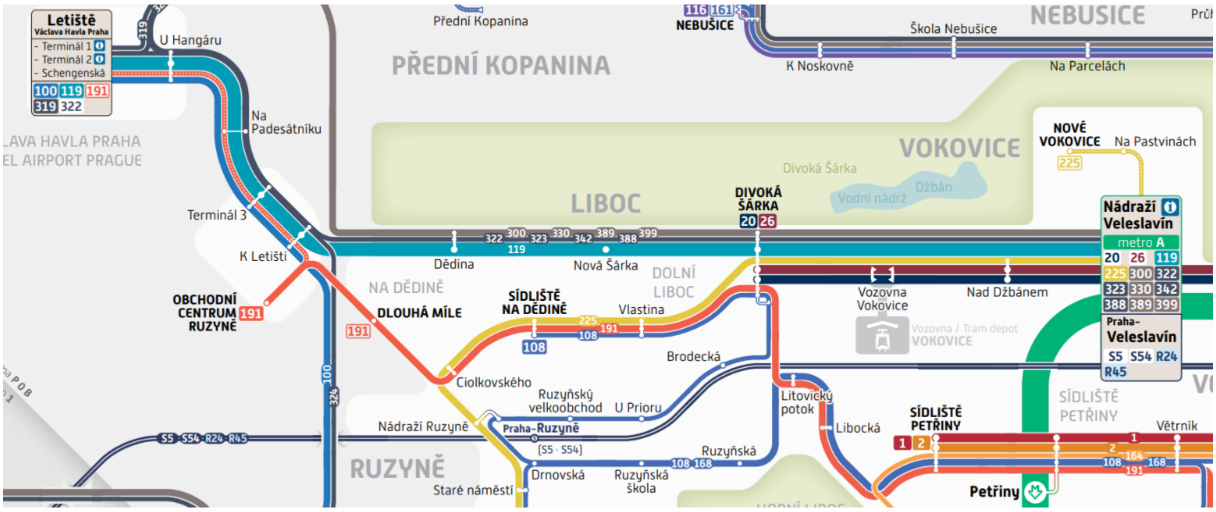

Figure 8: The scheme of public transit routes operating in the research area. [PID]

There are a total of 2 tramway routes, 2 city bus routes and 8 regional bus routes servicing the area. This section provides detailed descriptions of services by each transportation mode.

Trams

The tramway service on Evropská Street is provided by two tramway routes: 20 and 26. Route 20 is 17 km long and connects the Sídliště Barrandov in the south of Prague with Divoká Šárka. Route 26 is 21 km long and departures from Nádraží Hostivař in the southeast of Prague. The headway of each of the routes during the peak hours is 10 minutes, with both routes complementing each other and making it 5 minutes of subsequent headway. The 5 km long tramway track on Evropská Street services 11 stops and is terminated at the double-track balloon loop at Divoká Šárka.

In July 2022, the construction works on tramway track extension began. The tramway will be extended from existing tram loop Divoká Šárka to a new tram loop Dědinská. The newly planned double-track tram line will be 2.3 km long and will have 5 stops along the route [16]. The track will be headed straight from Divoká Šárka to Evropská at Vlastina intersection, where it will turn left to Vlastina Street. At the end of Vlastina Street, the track will turn right to the Drnovská Street where it will terminate at a newly built reversing loop Dědinská. Zoning plan also features the potential extension of the tramway track from Dědinská to Dlouhá Míle transfer center and further to Terminal 3. The planned tramway track is marked in red in the Figure 9.

Figure 9: The plan of the tramway extension from Divoká Šárka to Dědina. [DPP.cz]

Subway

The first 3.5 km of Evropská Street from Vítězné náměstí copies the track of subway line A with 3 stations enabling the transfer between trams and subway. Line A is a 17 km long subway route connecting Depo Hostivař in the southeast with the Old Town and the Motol University Hospital in the west part of the city. The Nádraží Veleslavín station is especially important as it provides a major transfer hub for commuters from western part of Prague and Central Bohemia Region, and those commuting from/to the Václav Havel Airport Prague. This hub enables the transfer between subway, trams, buses, and trains.

Bus transit

The bus transit operates mainly in the west part of Evropská Street as the eastern part is served by tramways and subway. The most frequent bus route operating on Evropská Street is route 119 connecting Nádraží Veleslavín station with Václav Havel Airport Prague. The headway of route 119 in peak hours is 3 minutes, following the arrivals of each subway train and trying to accommodate the high demand for trips to the airport. Route 119 is an express route with only 5 intermediate request stops along the way to the airport.

The missing high-capacity service (train, subway), which would connect the city with the airport, is going to be partly compensated in 2024 by dispatching new 24m long bi-articulated trolleybuses to replace standard 18m long articulated buses on route 119 [17]. Moreover, by 2029 there should be a modernized double-track railway from the Masarykovo nádraží station in the center of the city, heading via Nádraží Veleslavín station to the airport [18].

The rest of the bus transit in the area consists of less frequent routes 108, 191 and 225, which service mainly the residential areas south of Evropská Street.

Table 2: Public transit services provided on Evropská Street.

Type of PT	Route	Destination	Headway in peak hours
TRAM	20	Sídliště Barrandov / Nádraží Veleslavín	8 min
TRAM	26	Nádraží Holešovice / Nádraží Veleslavín	8 min
BUS	119	Airport / Nádraží Veleslavín	3 min
BUS	225	Velká Ohrada / Nádraží Veleslavín	10 min
REG. BUS	300	Kladno / Nádraží Veleslavín	15 min
REG. BUS	322	Slaný, AN / Nádraží Veleslavín	60 min
REG. BUS	323	Koleč / Nádraží Veleslavín	60 min
REG. BUS	330	Kladno / Nádraží Veleslavín	15 min
REG. BUS	342	Slaný, ŽST / Nádraží Veleslavín	30 min
REG. BUS	388	Slaný, Arb. / Nádraží Veleslavín	30 min
REG. BUS	389	Louny / Nádraží Veleslavín	30 min
REG. BUS	399	Smečno / Nádraží Veleslavín	15 min

Regional buses

The Nádraží Veleslavín transfer center is a terminal station for 8 regional bus routes arriving from west part of Central Bohemia Region. The most important destinations of these commuter services include the cities of Kladno, Slaný, and Louny. The most frequent services are routes 300 and 330 leaving Nádraží Veleslavín every 15 minutes during the peak hours. These regional buses usually have two more stops along Evropská Street – Divoká Šárka and Navigátorů, before they leave Prague and head towards highway D6 or D7. Regional buses are part of the PID (Prague's Integrated Transport) system servicing the city of Prague and Central Bohemian Region, which means they share the same fares and transport conditions as the bus transit in Prague.

Railway

The research area also includes a railway. The single-track non-electrified railway line nr. 120 connects the Praha-Masarykovo nádraží station in the city center with the city of Kladno, 20 km northwest of Prague. This line is the backbone of the passenger rail transport in this area. There are two railway stations in the area: Praha-Veleslavín and Praha-Ruzyně. The express trains to Rakovník (R24) leave from Veleslavín station every 2 hours, the regional expresses to Kladno (R45) run every hour as well as local trains to Kralupy nad Vltavou (S5).

From 2023 to 2029, the construction works will take place on the railway to build a modern, frequent, and high-capacity connection to the Václav Havel Airport Prague and Kladno [18]. This project includes double tracking and electrification of the railway. Once the reconstructed railway will be opened, significant changes to bus services in the area will be made. Bus route 119 will be shortened and will not service the airport as all passengers will be taking trains. Also, regional buses will be rerouted and will not be servicing Nádraží Veleslavín, which will be mainly used just for transfer between subway and trains.

Public transit schedule adherence on Evropská Street

To analyze the performance of TSP on Evropská Street, data about the delays of each route was obtained. Regionální organizátor Pražské integrované dopravy (ROPID), the regional transit agency responsible for providing public transit in Prague and Central Bohemian Region, provided data about the delay of each service at each stop in the research area (Nádraží Veleslavín –> Divoká Šárka –> Navigátorů). Based on this data, we could tell in which sections of Evropská Street were buses / trams delayed the most and where is the potential for TSP implementation to improve on-time performance.

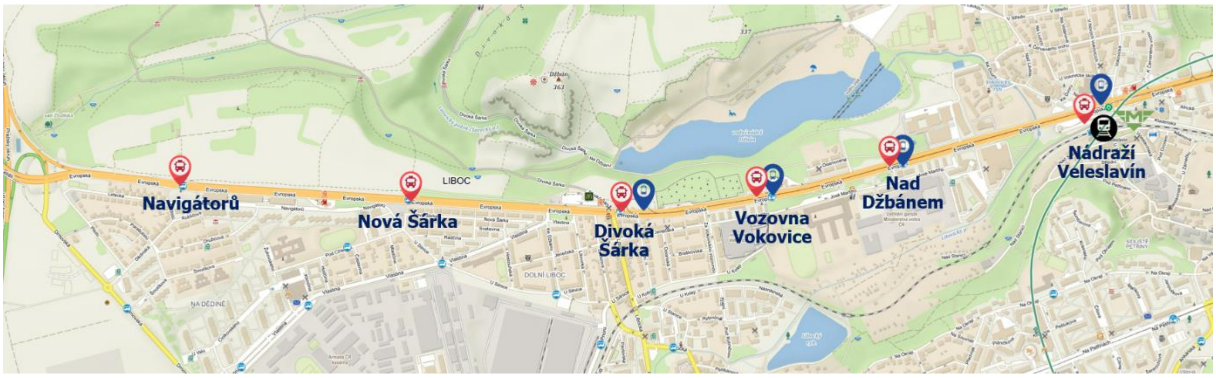

Figure 10: Bus and tram stops in the research area. RED = bus stops, BLUE = tram stops [Mapy.cz]

The provided data was collected by check-in system located on board the transit vehicles driving through Evropská Street. For particular route and its stop, the dataset provided the scheduled arrival, actual arrival and delay. Dataset included statistics of routes 20 and 119 measured in May 2022. For this research, only evening peak hours (4:00 p.m. to 6:00 p.m.) on workdays (the busiest time period) were evaluated.

Date	Route	Current Stop	Next Stop	Scheduled Arriva	Actual Arrival	Delay
1.5.2022	119	Nádraží Veleslavín	Divoká Šárka	15:58	15:59:47	1:47
1.5.2022	119	Nádraží Veleslavín	Divoká Šárka	16:13	16:14:13	1:13
1.5.2022	119	Nádraží Veleslavín	Divoká Šárka	16:28	16:29:22	1:22
1.5.2022	119	Nádraží Veleslavín	Divoká Šárka	16:43	16:44:13	1:13
1.5.2022	119	Nádraží Veleslavín	Divoká Šárka	16:58	16:58:19	0:19
1.5.2022	119	Nádraží Veleslavín	Divoká Šárka	17:13	17:14:48	1:48
1.5.2022	119	Nádraží Veleslavín	Divoká Šárka	17:28	17:28:47	0:47

Figure 11: Screenshot of the provided dataset.

After data filtering, the delays were converted into minutes and the average delay of each route at a particular stop was calculated. Calculations were done for both directions, i.e., from Nádraží Veleslavín westbound and from Navigátorů stop eastbound.

Westbound

The first to be evaluated was route 119 in direction to the airport (westbound). From over 900 connections, 94% of them departed from Nádraží Veleslavín on time (0–1 minute delay). At the next stop (Divoká Šárka), only 45% of connections were on time and the average delay increased to 1 minute and 52 sec. At the rest of the stops on Evropská Street, the average delay increased less significantly. Only 33% of connections arrived to Návigátorů stop on time, with most of the services having delay of 2 minutes, while the headway of route 119 is 3 minutes.

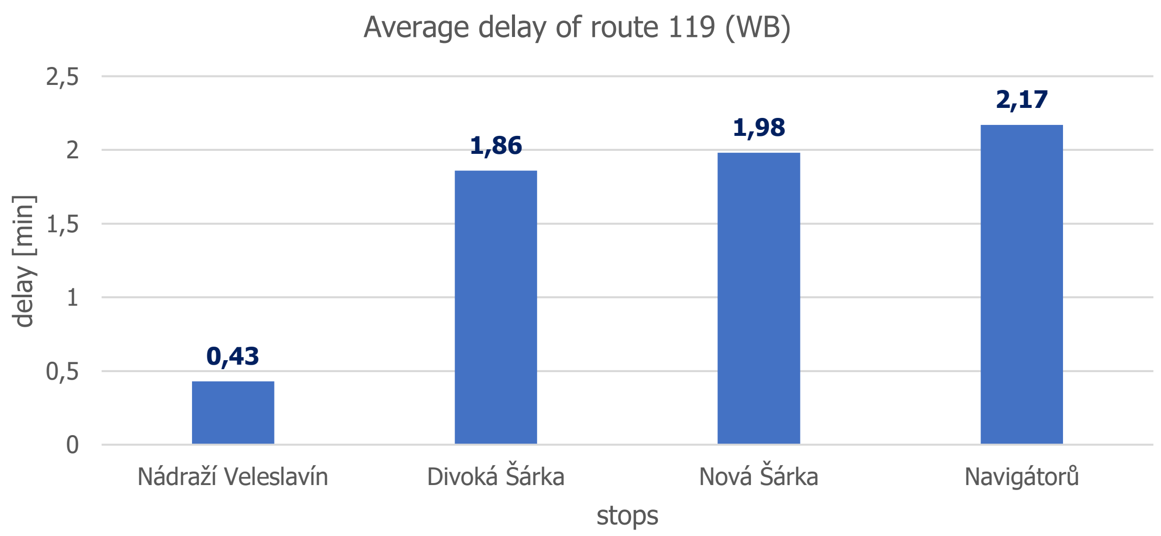

Figure 12: The average delays of route 119 at each stop along the Evropská street (WB).

The next route for evaluating the westbound direction of Evropská was the tramway route 20. This route arrives to Nádraží Veleslavín stop after 15 km and 40 minutes long drive through the city. That means a bigger chance that the service is going to be delayed. As seen at the

Figure 13, the average delay at Nádraží Veleslavín was already 4 minutes and 21 seconds. Out of 158 analyzed connections, only 13 arrived without delay. At the next stop, Nad Džbánem, the delay slightly increased, but for the rest of the route was the delay increasing and at Divoká Šárka 48 trams (31%) arrived on time. This result may be a combination of factors: 1) lower ridership at the end of the route means faster boarding and alighting process, which results in lower dwell time and thus higher average speed, 2) TSP for trams becomes effective and reduces the delay, 3) travel times between last stops are overestimated in the time schedule.

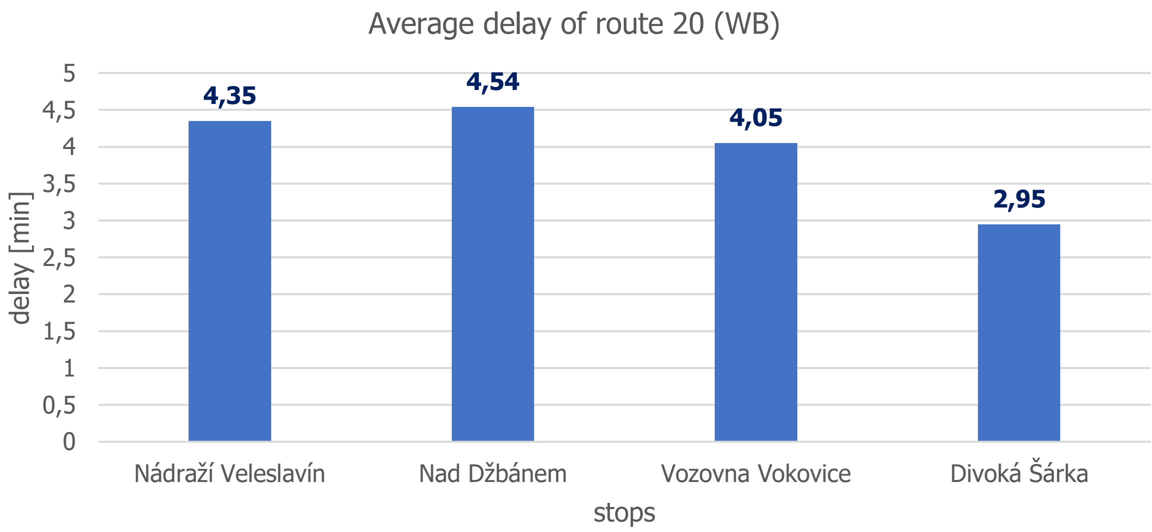

Figure 13: The average delays of route 20 at each stop on Evropská Street (WB).

Eastbound

As for the direction to the center of Prague (eastbound), route number 119 approaches the city via dedicated bus lane on Evropská Street. This results in a relatively low average delay at two first stops at Evropská Street (approximately 2 minutes). Going further to the east, the bus is getting a little more delayed while it has to pass through two busy signalized intersections (Evropská at Libocká, Evropská at Veleslavínská), where no bus priority is implemented. As seen in the Figure 14, the final delay of buses arriving to Nádraží Veleslavín is just about 2 minutes (37% of connections arrived on time, 31% 2 minutes delayed, and 30% 3 minutes delayed).

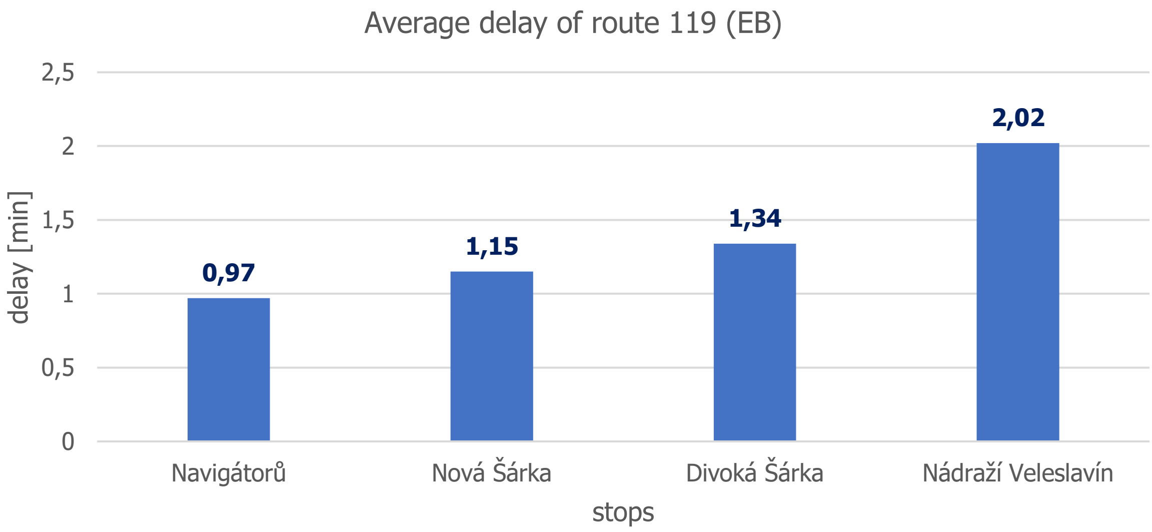

Figure 14: The average delays of route 119 at each stop on Evropská Street (EB).

The tramway route 20 departing from Divoká Šárka eastbound, has average delay at first couple of stops on Evropská Street considerably low (less than 1 min means there is no delay because the lowest time unit in time scheduling is 1 min). All trams in this section are prioritized at the intersections, meaning that 91% of connections arrive to Nádraží Veleslavín on time.

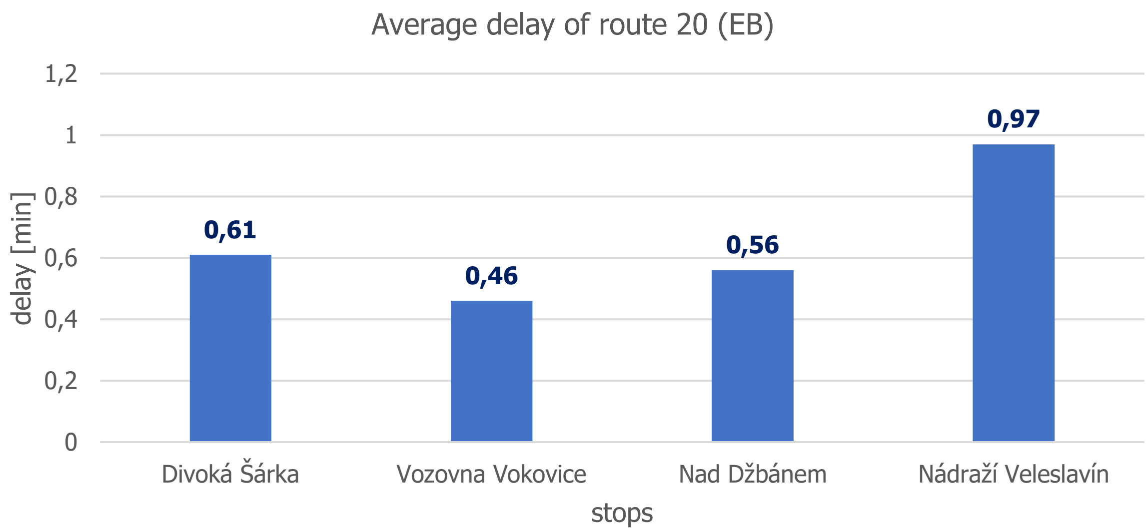

Figure 15: The average delays of route 20 at each stop on Evropská Street (EB).

To summarize the findings from this section, we can say that trams heading westbound are able to reduce their delays and trams heading eastbound experience basically on-performance, mainly thanks to the TSP. Buses on the contrary increase the delay in both directions and there is a potential for improvements.

Public transit ridership on Evropská Street

When assessing the performance of TSP and its impact on other transport modes, one of the factors to compare is the occupancy of each mode. The average occupancy of cars in Prague's city center in 2021 was 1.3 person/vehicle according to TSK [13]. This means that most of the cars were single occupied vehicles (SOVs). To compare this with transit vehicles occupancy, the on occupancy of route 119 was provided by the transit operator DPP. This data was collected in May 2022 by automatic passenger counting (APC) system on-board the transit vehicles. The provided datasets consisted of columns with number of route, date, time and the number of passengers aboard the vehicle at each stop. To be consistent with other data used in this research, only counts from the evening rush hour on weekdays were included.

Route 119 is one of the busiest bus routes in Prague as it provides the main connection to the airport. It is operated by 18m long articulated buses with the total capacity of 161 passengers. As seen in Table 3, the average occupancy at the departure station is approximately 20 passengers in direction to the airport, respectively 26 passengers.

Occupancy rates of other transit routes were not provided, but it is to be noted that Nádraží Veleslavín is one of the busiest transfer centers in Prague. According to TSK statistics, its metro station accommodated each day 18000 arriving passengers, resp. 21000 departing [19].

Table 3: The average occupancy of buses on route 119 in both directions.

OCCUPANCY OF ROUTE 119 [number of passengers]	Nádraží Veleslavín	Divoká Šárka	Nová Šárka	Dědina	K Letišti	Terminál 3	U Hangáru	Terminál 1	Terminál 2	Airport
DIRECTION	–> AIRPORT									
MAX	47	43	41	40	36	36	36	35	10	0
AVERAGE	19	17	15	13	12	12	11	6	1	0
DIRECTION	<– NÁDRAŽÍ VELESLAVÍN									
MAX	0	24	57	59	61	64	72	74	75	70
AVERAGE	0	7	18	20	22	22	25	25	26	26

Chapter 4: MICROSCOPIC TRAFFIC SIMULATION

The main objective of this thesis is to evaluate existing TSP on Evropská Street and subsequently propose improvements to this system. For this purpose, a microsimulation model of traffic on Evropská Street was created. In the following chapter, the process of designing the model is described including the data sources, model validation and simulation configuration.

Traffic microsimulation was chosen as a convenient tool for evaluating of TSP measures as it enables a modeling of individual vehicle movements on a second or subsecond basis. It is a commonly used method for assessing the traffic performance of highway and street systems, transit, and pedestrians [20].

4.1 Microsimulation Software

The tool that was chosen for microsimulation of traffic in this thesis is PTV VISSIM, a software developed by German company PTV in Karlsruhe. This software is a market leader in microsimulation of traffic in cities as it allows a various range of applications. The software provides a virtual representation of a transportation network, allowing users to simulate different traffic scenarios and evaluate their impact on traffic performance. PTV VISSIM is used to simulate a wide range of transportation systems, including road networks, public transportation, pedestrian and bicycle traffic, and more. The software provides detailed information on traffic flow, including speed, travel time, and vehicle interactions, which can be used to inform transportation planning and decision-making. It is widely used in academia, transportation planning and engineering, and by government agencies around the world [21].

4.2 Simulation Area

The focus of this research is aimed at the 3.5 km long section on the very west of Evropská Street. This area was chosen for the microsimulation as it is a busy multimodal area that includes multiple signalized intersections with a tramway track in median and dedicated bus lanes in the right eastbound lane. The Street is known for its high peak hour traffic volumes with about 16,000 of veh/hour in each direction as well as extensive public transit operation. About 10 bus routes and 2 tramway routes driving through Evropská Street to access the Nádraží Veleslavín transfer center. The above-mentioned facts make this area a good testbed for microsimulation of traffic flows, traffic lights control and transit signal priority measures.

4.3 Data Sources

The first step in creating a microsimulation model is to collect data on the road network and traffic flows in the study area. This includes information on road geometry, traffic volumes, vehicle types, and travel patterns. In this research, data from a variety of sources was collected, including traffic surveys, travel forecasts, Bluetooth sensors, GIS data from public transit vehicles, as well as field measurements.

Traffic flow data

The traffic volumes data on Evropská Street was provided by Technická správa komunikací (TSK Praha), a city-owned company responsible for road maintenance and traffic studies in Prague. The provided package includes volumes from 2022 as well as traffic flow forecasts for 2030. The provided data consists of all-day traffic on an average day in 2022. For the purposes of our simulation, the 8% rate from all-day traffic was derived to represent the usual traffic in peak hours.

The traffic forecasts for 2030 are based on Prague's traffic demand model and were provided in two variants – with / without completed Prague's Outer Ring Road (Pražský okruh – D0). According to the level of completion of the Ring Road (sections 518, 519, 520), the traffic volumes in the area will decrease (completed D0) or increase D0 (incomplete). For each signalized intersection on Evropská Street, a scheme of the intersection with marked movements and their traffic flows was provided.

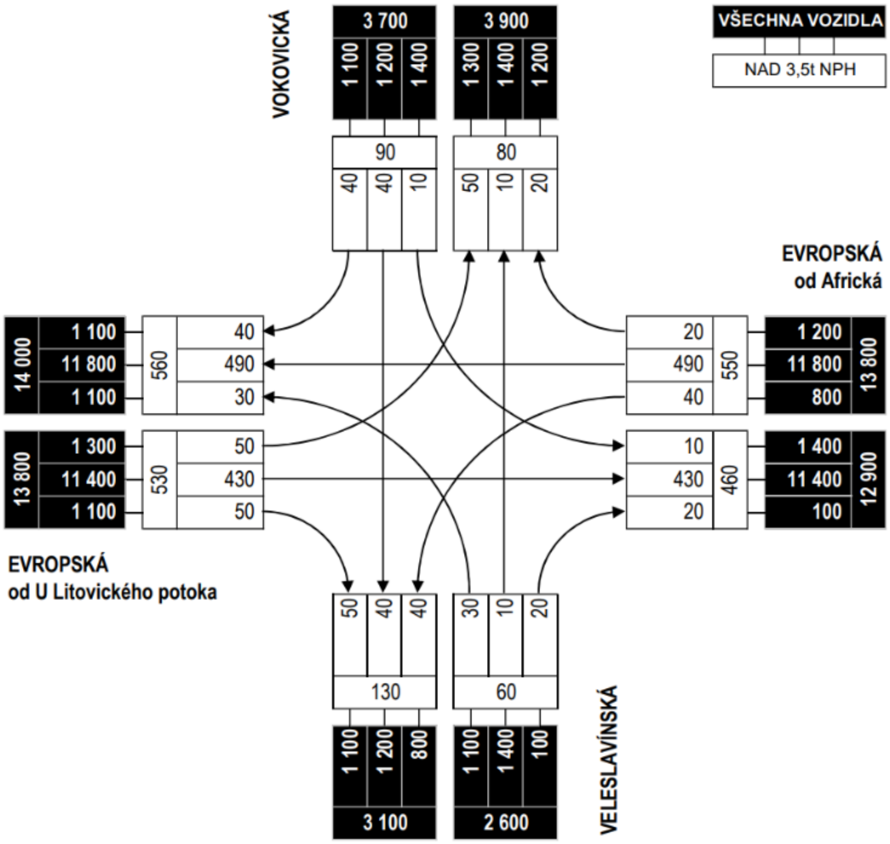

Figure 16: An example of the provided scheme of flows in the intersection. [TSK]

Geometric Data

An integral part of the data package required for modelling an accurate simulation is the road network data, which consists of all the lanes, intersections, bus stops, tramway stops, and other relevant parts of the research area. To create the model with the most accurate geometry of physical infrastructure as possible, a drawing of the surface situation was downloaded from Geoportal Prahy, a web with open geographical data [20]. Together with surface situation, a scaled aerial imaginary of the whole research area was downloaded and imported to the microsimulation software as a background. The lane configurations and traffic signal timings were confirmed or revised based on field observations.

To model a planned tramway extension from Divoká Šárka to Dědina, a coordinated situation plan was downloaded from the web of DPP (Prague's transit operator) [16].

Traffic control data

Technická správa komunikací (TSK), a Prague's city company responsible for signal controls operation, provided information that all signalized intersections in the research area use the dynamic signal control system. This feature allows the controller to modify the signal plan in real time or create a new one according to current traffic demands detected by traffic detectors. Moreover, the signal priority for tramways on Evropská Street is incorporated into this system. Tramways get green signal when they're approaching the intersection, so they do not have to stop, and their travel times improve. However, public transit and regional buses are not included in this system and have to wait for green signal as regular cars.

Because of dynamic control, each cycle has a different number and sequence of phases, and different lengths of green and red signals can be executed according to the programming control logic. The time duration of green signal therefore changes depending on the current demand and traffic intensity. To simplify this process and to avoid complicated importing of programming logic into VISSIM, a field observation was conducted to measure typical lengths of phases in rush hour. These signal timings were then inserted into VISSIM to model a fixed-time control.

Public transit data

The data on the public transit operated on Evropská Street was obtained online on the website of Regionální organizátor Pražské integrované dopravy (ROPID), a city-owned transit agency responsible for organizing and coordinating transit system in Prague and Central Bohemian Region. The most important data for the research consists of the routing and frequency of each individual bus and tramway service on Evropská Street.

Bluetooth data

An important source of data needed especially for model validation, was provided via Smart Bluetooth sensors by company CAMEA installed along the Evropská Street. These sensors detect all devices with active Bluetooth and record its unique MAC address and timestamp. Based on the location of each detector and the times when each detection was recorded, we can pair up records with same MAC addresses (meaning it is the same device) and calculate the travel time between particular pair of detectors. These calculated travel times tell us how long the car drives between these sensors, which will be later used for comparison of the travel times obtained from the model.

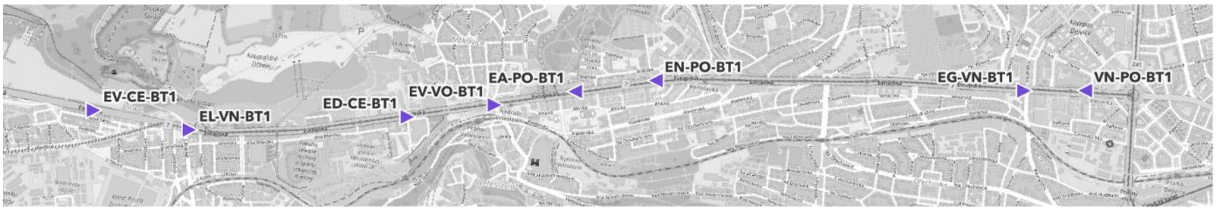

Figure 17: Locations of Bluetooth sensors on Evropská Street.

4.4 Model Design

Creating a microsimulation model in VISSIM involves several steps, including defining the road network, creating vehicle inputs and assigning routes, setting traffic signals, defining conflict areas and priority rules and many more. When the network is defined and the traffic is inserted, the next step is configuration of simulation speed, data collection period and number of runs. Subsequently, the outputs that you want to collect need to be selected (travel times, queue lengths, traffic volumes, etc.). Once the model is established, we can proceed with running the simulations and examining the outputs. Model should be validated with the real-world measurements before proceeding with the evaluation of results.

This chapter follows the steps of constructing the microsimulation model of the western part of Evropská Street in Prague. The creation of the model 0, which represents the current state of infrastructure, is described. In next phases, this model is modified according to future infrastructure plans and traffic volumes, which results in creation of three additional models.

Network creation

The first step was to create the network in VISSIM. This involves importing the road network data. The network must be designed to accurately reflect the real-world road network, including the number of lanes, speed limits, and traffic signals.

To define the road network, the background aerial photo was imported into VISSIM and the geometry of the roads, including the number of lanes and their width was created using the tool named "Links" and "Connectors". Once the links were created, speed limits were assigned to the network according to signage on Evropská Street. In the intersections and areas with sharp turns, reduced speed areas were inserted to simulate the same deceleration as experienced by cars.

Traffic assignment and routing

The next step was to insert vehicle inputs based on the traffic volumes provided by TSK. The inputs to the simulation model are based on the peak hour volumes of an average working day. These volumes were calculated as 8% of the average all-day traffic (ADT) volumes collected on Evropská Street.

Once the vehicles were inserted to the network, the next step was to assign them to specific routes in intersections according to schemes provided by the TSK. This was done by selecting the tool "vehicle route decision" and specifying the percentage of vehicles in the intersection going straight or turning right / left.

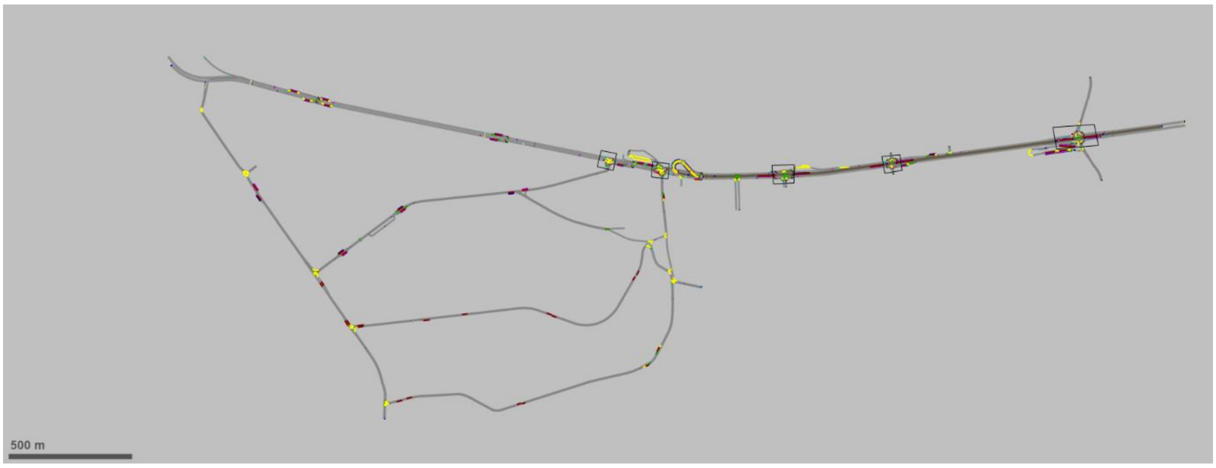

Figure 18: Screenshot of the whole road network created in VISSIM.

Pedestrians and crossings

Another type of traffic input that needed to be inserted into network are pedestrians. VISSIM offers the tool "areas" to model pavements and public transit stops / waiting areas. Pedestrian inputs were placed evenly to the areas with most anticipated pedestrian movements (close to public transit stops). Pedestrian crossings with traffic lights were modelled using detectors of movement of pedestrians as a replication of call buttons.

Public transit routes

The crucial part of designing the model was the simulation of public transit. Both tramway routes, two city bus routes and seven regional bus routes were modelled in both directions. The tool of "public transit lines" allows the author to set the average occupancy of vehicles and departure times from the stations according to real-world schedule. The next step was inserting of tramway and bus stops into the network and assigning them to particular stops.

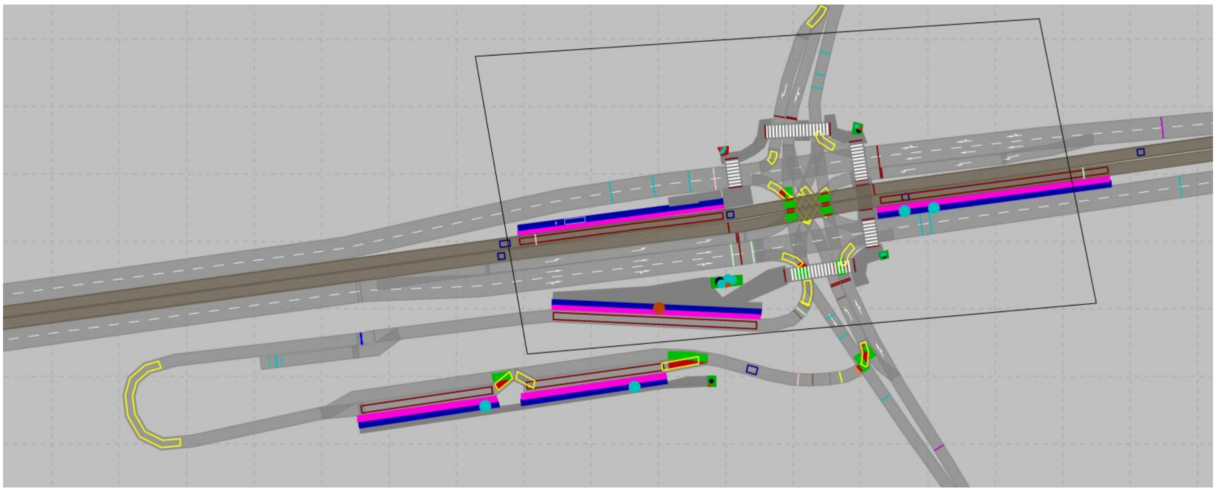

Figure 19: A detail of Nádraží Veleslavín transfer center as modelled in VISSIM.

Dedicated bus lane implementation

On weekdays (from 6:00 a.m. to 8:00 p.m.), the right eastbound lane of Evropská Street (in 5 separate sections) operates as a dedicated bus lane (with taxi vehicles and cyclists permitted). Since the analysis time periods were for the peak hour, the implementation of the bus lane was an important aspect of the network coding. VISSIM allows particular lanes of a link to be closed to certain vehicle types. In this research the right lane was closed to all "non-BUS" types.

Public transit dwell time

The bus and tramway dwell times at each stop vary due to different frequencies of boarding and alighting passengers. To simplify this in the simulation, all bus and tramway dwell times at stops on Evropská Street were set to have a minimum distribution of 20 seconds ±. The exception was made for regional buses heading out of Prague because their boarding is carried only through front doors and takes more time. This dwell time was estimated to have a minimum distribution of 40 seconds±.

Speed distributions

Stochastic distributions of observed speeds are defined for each vehicle type within each vehicle composition. Observed speeds were used to create distribution for several locations of Evropská Street since speeds vary there. This speed is generally higher than the posted speed and may be defined as the free-flow speed for the highway. If not hindered by other vehicles, a driver would travel at his desired speed (with a small stochastic variation).

Table 4 defines the speed distributions assigned to each vehicle class in the model. The speed at areas with restricted speed (areas close to intersections etc.) were modified by the function "desired speed decision".

Table 4: The speed distributions assigned to each vehicle class.

SPEED DISTRIBUTIONS	SPEED [km/h]
CARS/HGW ON EVROPSKÁ	70
CARS/HGW ON SIDE ROADS	50
TRAMWAYS	50
BUSES	50

Traffic signal control settings

After defining the traffic volumes and their routes, the behavior of cars must be managed by defining priority rules, stop signs and most importantly the traffic signals. As mentioned earlier, the signal control on Evropská Street uses dynamic phasing based on complex logic coding that would be very demanding to replicate in VISSIM. For the simplification of this process, usual timings patterns in rush hour were observed during field trip on Evropská Street and inserted into VISSIM using the "VISSIG" tool for signal control simulation. This tool is the easiest way to create a fixed-time signal control with desired signal groups and signal plan that matches the observed signal timings.

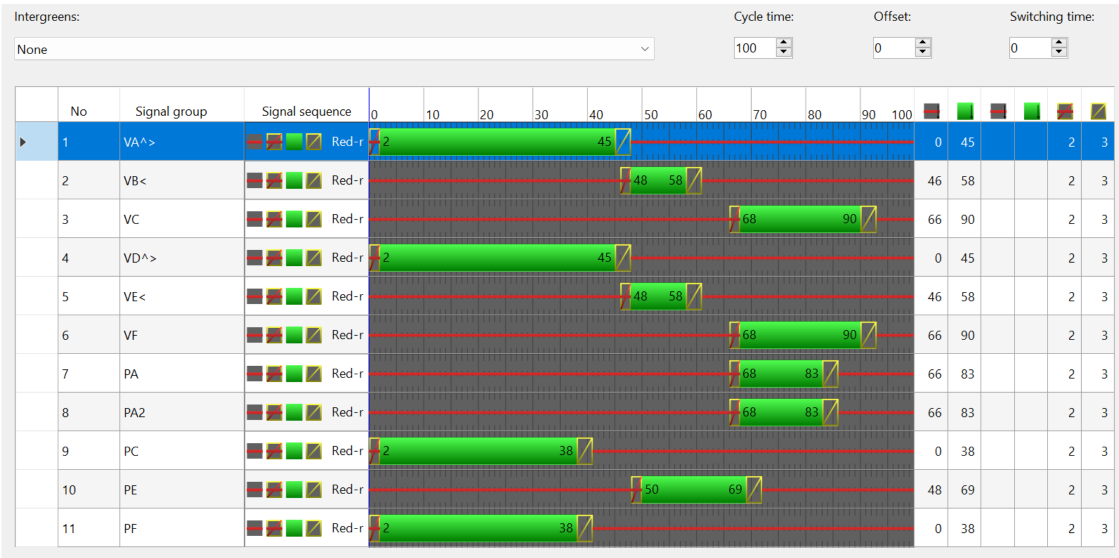

Figure 20: The signal plan created in modul 'VISSIG'.

Transit signal priority implementation

To simulate the tramway signal priority at intersections, a couple of detectors in both directions of the flow were inserted. The first detector was inserted on the tramway track 50 meters upstream of the intersection stop line and the second detector at downstream where the tram left the intersection. After tram is detected by the first detector, all conflict flows at the intersection get the red signal and the tram can pass the intersection without stopping. This is a simplification of how the real-world passive detection of trams via trolley wires works.

Driver behavior parameters

The driver behavior in VISSIM is modeled through the car following and the lane change models. The driving behavior is linked to each link by its „link type".

VISSIM includes two car-following models – urban driver (Wiedemann 74) and freeway driver (Wiedemann 99). The basic concept of both models is that the driver of a faster moving vehicle starts to decelerate as he reaches his individual perception threshold to a slower moving vehicle. Since the driver cannot exactly determine the speed of that vehicle, his speed will fall below that vehicle's speed until he starts to slightly accelerate again after reaching another perception threshold. The core execution or logic in Wiedemann 99 is the same; however, some of the thresholds are calculated differently from the Wiedemann 74 model. The Wiedemann 74 model is suggested for use in urban conditions, whereas Wiedemann 99 is suggested for use on freeways [23].

In this simulation, both driver types were used. For the major flows on Evropská Street the freeway driver behavior with free lane selection function was chosen. For the rest of the network, the urban (motorized) behavior was selected.

4.5 Model Calibration

The objective of model calibration is to obtain the best match possible between model performance outputs and the real-world data observed during field measurements. Within this section, the model outputs were evaluated against empirical data to verify their consistency with acceptable standards. To achieve this, validation criteria endorsed by the Federal Highway Administration (FHWA) were employed in this study [20]. Below is a list of criteria and the process of their verification.

Goal 1: Travel times of cars achieved in the model to be within 15 percent (or one minute, if higher) for the selected segments of Evropská Street.

To compare the travel times obtained from simulation outputs with the real-world, the data from Bluetooth detectors installed along Evropská Street was used. The Bluetooth sensors on Evropská Street are part of the data collection project by the company CAMEA. By matching detection records from two different detectors by unique mac addresses of each device, travel times between these two detectors were calculated. For one particular pair of detectors which were 2,2 km apart, the average time of 3.5 minutes was calculated. The results from VISSIM showed the average travel time on this segment to be 3.8 minutes. The difference is 9%, meaning that this criterium passed.

Goal 2: Modeled volumes to be within 10 percent of field measurements.

This criterion was verified in VISSIM by data collection point placed on the westbound approach of the intersection 4 (6.123 Evropská at Libocká Street). The average counts showed 1102 vehicles/hour, whereas the field measurements conducted by TSK on May 16, 2022 counted 1223 vehicles/hour in the peak hour. The difference is exactly 10%, meaning the modeled volumes were within the acceptable difference from real-world traffic volumes.

Goal 3: Travel times of public transit achieved in the model to be within 15 percent of the real-world travel times.

The average travel time of route 119 from Nádraží Veleslavín to Divoká Šárka in the model was 212 seconds. According to transit agency PID, the scheduled travel time is 3 minutes, which can be 150-230 seconds (the lowest time unit in the schedules is 1 minute). This means that the simulated value is perfectly within the real-world conditions.

4.6 Simulation Configuration

Once the calibrated model was established, each model was run 10 times with the same set of random seeds. The random seed affects the realization of the stochastic quantities in

VISSIM, such as vehicle headways at input links and behavioral attributes. For congested corridors, at least five seed runs are generally recommended [20]. The results presented in Chapters 5 and 6 are based on the average values from 10 simulation runs.

The total time period of the simulation was set to 5400 seconds (90 minutes), from which only 3600 seconds was evaluated. This is a standardized method recommended by FHWA. The evaluation (collection of statistics) started from the time of 900 seconds and ended at 4500 sec. The first 900 seconds is not evaluated because of the time needed for the network to fill with the traffic (warm up period) and the last 900 seconds is the time needed for the traffic to cool down (to reach their destinations).

4.7 Simulation Outputs

Before proceeding with running the simulation, the last step is selecting outputs to be collected for evaluation. For this research, the evaluation of nodes (intersections) and vehicle travel times is essential. Other attributes that were selected include data collection points and link volume counters necessary for validation of the model.

Table 5: Outputs selected for evaluation.

	Collect data	From-time	To-time	Interval	
Area measurements	☐	0	99999	99999	
Areas & ramps	☐	0	99999	99999	
Data collections	☑	900	4500	99999	
Delays	☑	900	4500	99999	
Links	☑	900	4500	99999	More...
Meso edges	☐	0	99999	99999	
Nodes	☑	900	4500	99999	More...
OD pairs	☐	0	99999	99999	
Parking lot groups	☐	0	99999	99999	
Parking lots	☐	0	99999	99999	
Parking routing decisions	☐	0	99999	99999	
Parking spaces	☐	0	99999	99999	
Pedestrian Grid Cells	☐	0	99999	99999	More...
Pedestrian network performance	☐	0	99999	99999	
Pedestrian travel times	☐	0	99999	99999	
Queue counters	☐	0	99999	99999	More...
Vehicle inputs	☑	900	4500	99999	
Vehicle network performance	☑	900	4500	99999	
Vehicle travel times	☑	900	4500	99999	More...

Chapter 5: INITIAL SIMULATION MODELS

In the first phase of modelling, four initial models were created. These models differ in the state of infrastructure and traffic volumes (years 2022 and 2030).

In this chapter each model is described, and its outputs are analyzed. Critical points on the network are identified and the impact on all modes of transport is evaluated. The comparison of travel times achieved in each model is provided at the end of the chapter. Based on the findings in this chapter, improvements to transit signal priority system are suggested.

5.1 Terminologies

Before starting the evaluation of each model, terminologies used in the evaluation analysis need to be explained, because PTV VISSIM uses specific attribute values to evaluate the results.

VehDelay: Delay in seconds that it takes to leave the node (intersection). The counting of delay starts from crossing the start section until leaving the node.

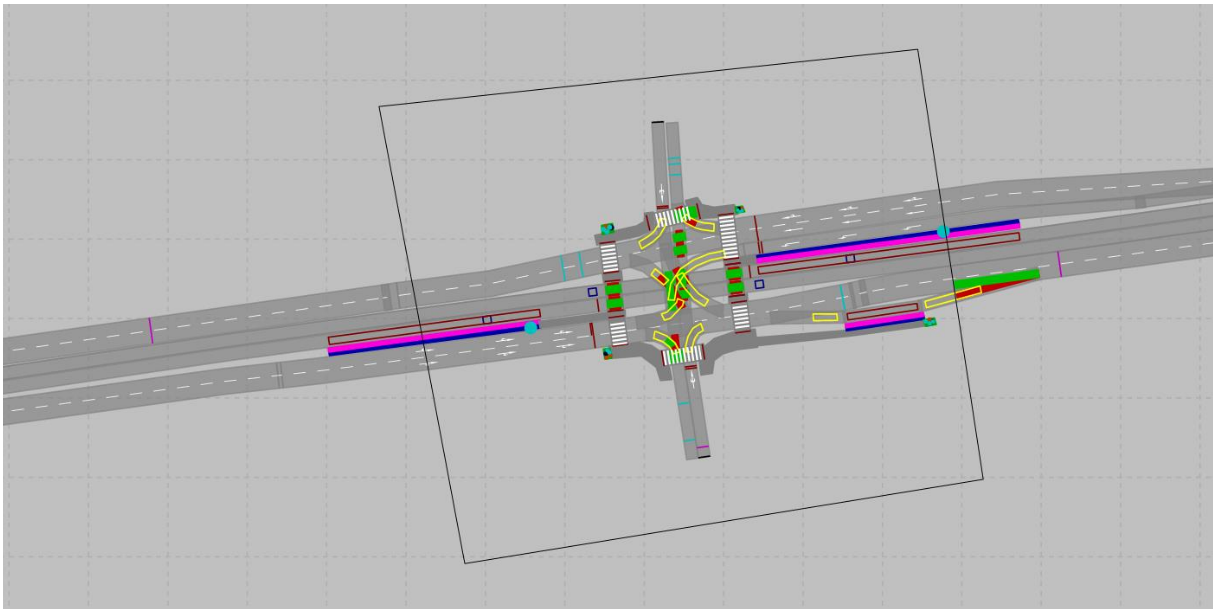

Figure 21: A screenshot showing the boundaries of “node” for evaluation.

Level of Service (transport quality): The levels of transport quality A to F, with A being the best (free flow) and F = the worst (breakdown flow). It is based on the result attribute Vehicle delay (average). The LOS in VISSIM is the same as the LOS defined in the American Highway Capacity Manual (HCM) of 2010 [23].

Table 6: Classification of Levels of Service according to HCM.

	Signalized intersection	**Non-signalized intersection**
LOS_A	Delay < 10 s or no volume, as no vehicle is moving, also due to traffic jam	
LOS_B	> 10 s to 20 s	> 10 s to 15 s
LOS_C	> 20 s to 35 s	> 15 s to 25 s
LOS_D	> 35 s to 55 s	> 25 s to 35 s
LOS_E	> 55 s to 80 s	> 35 s to 50 s
LOS_F	> 80 s	> 50 s

To make the evaluation of results easier to read, each intersection (node) has been given a number that will be used as a reference to particular intersection instead of the full name of the intersection. See the Figure 22 with the location of evaluated intersections.

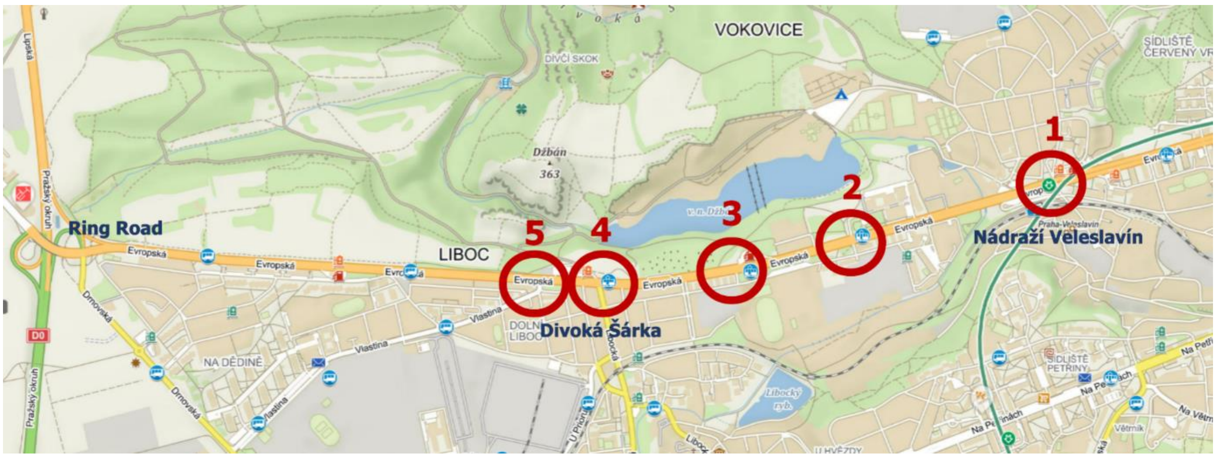

Figure 22: Location of the evaluated intersections. [Mapy.cz]

5.1 Model 0: 2022 Current State

The first model represents the current state of infrastructure with traffic volumes that were collected in 2022. The existing road in the Divoká Šárka section is currently undergoing a reconstruction as the tramway track is being extended. The purpose of developing this model is only to be able to compare the impact of newly constructed part of the tramway line on overall traffic on Evropská Street.

Simulation outputs

For each intersection, the delay and LOS of overall traffic, cars and public transit routes 20, 119 and 300 were evaluated. These routes were selected as they represent the most frequent services of each transportation mode.

Table 7: Evaluation of delays and LOS at intersections in Model 0.

MODEL 0: CURRENT STATE	NODES EVALUATION [sec]			ALL TRAFFIC	CARS	TRAM ROUTE 20	BUS ROUTE 119	BUS ROUTE 300
	intersection							
	1	Evr. at Veleslav.	Delay	26,16	24,99	20,36	60,64	54,17
			LOS	C	C	C	E	E
	2	Evr. at garáže MV	Delay	13,92	13,81	17,71	13,87	13,29
			LOS	B	B	B	B	B
	3	Evr. at Do Vozovny	Delay	10,42	10,26	17,72	10,07	9,44
			LOS	B	B	B	B	B
	4	Evr. at Libocká	Delay	13,01	13,04		15,17	13,75
			LOS	B	B		B	B
	5	Evr. at Vlastina	Delay	18,85	17,81		34,79	32,50
			LOS	B	B		C	C

As you can see in the Table 7, the busiest intersection in the area is intersection 1 (Evropská at Veleslavínská). At this intersection Evropská Street crosses two relatively frequent flows of Vokovická and Veleslavínská Streets. It is also an access point for buses to get in and out of the Nádraží Veleslavín transfer center. The exit of buses from the transfer center has been identified as the main bottleneck of the current network in terms of public transit operation (notice the LOS E obtained from the simulation outputs). Buses leaving the transfer center are turning left to Veleslavínská Street and then they have to immediately approach the left turning lane of the intersection 1. The distance between the point where buses leave the transfer center and the stop line of intersection (the length of the left turning lane) is about 22m, which is just enough to accommodate one articulated bus (route 119). The left turning movement here is besides buses also frequently made by other traffic and buses therefore have difficulties to leave the transfer center and access the turning lane. During the simulation, there were multiple cases of buses queuing before being able to leave the transfer center. For route 119, which leaves Nádraží Veleslavín every 3 minutes in peak hours, this generates delay immediately at the start of its route.

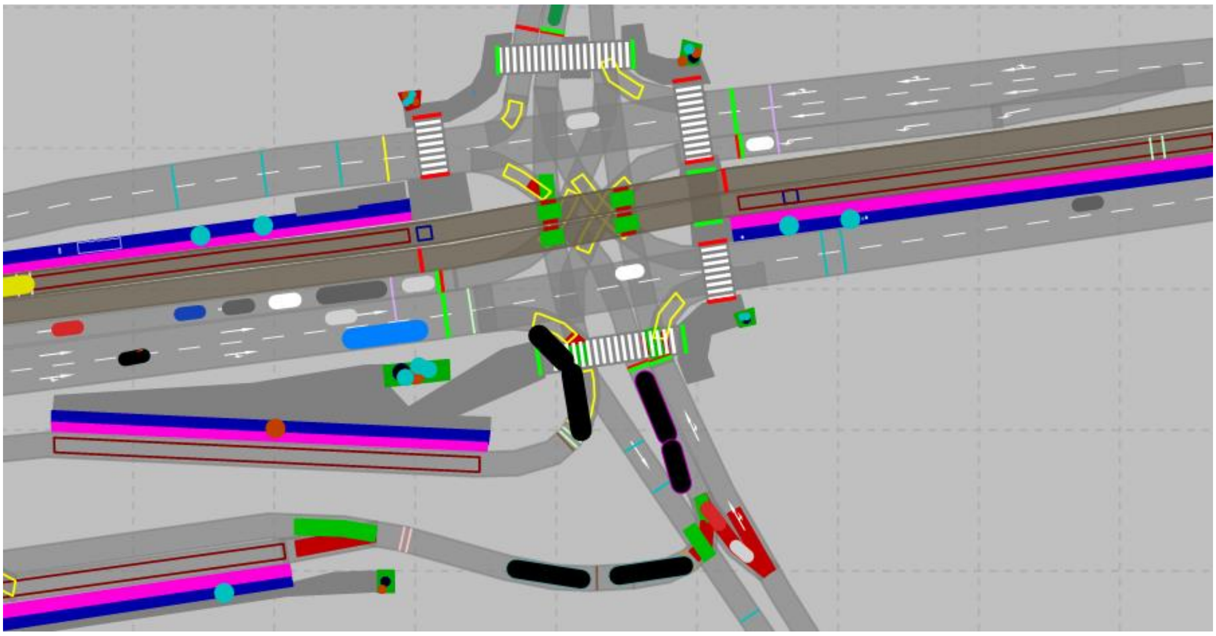

Figure 23: A detail from simulation shows buses queuing on the exit from the transfer center.

As for the rest of the intersections, the traffic seems to be relatively smooth and there are no significant delays for cars or public transit. This is particularly due to lower flows on colliding roads and also due to the fact that the assessed PT routes are only making through movement.

5.2 Model 1: 2022 with Tram Extension

The second simulation model was also based on 2022 volumes, but the infrastructure network is modified to include the planned tramway extension from Divoká Šárka to Sídliště Dědina. The construction of the extension began in July 2022 and is to be completed by the end of 2023. The tramway track will be firstly extended from the current reversing loop for another 200 meters further westbound and then will leave the route of Evropská Street to the left to Vlastina Street. The tram track will then be headed southwest for another 2 km to the area of housing estate Dědina, where new reversing loop will be built.

With the opening of extended tramway track, a new routing of tramway and bus lines will be introduced according to ROPID. This includes both tramway routes (20 and 26) being extended to a new terminal station Dědina and on the contrary two bus routes being shortened because their operation would duplicate the service of extended tramway routes. Bus route 225 will be now departing from Sídliště Na Dědině (instead of Nádraží Veleslavín) and will not be servicing Evropská Street. Bus route 108 will be shortened to Divoká Šárka and will not be operating on Vlastina Street. All these changes were reflected in the VISSIM model.

The main difference from the current design of Evropská Street is the organization of public transit operation at Divoká Šárka stop. Figure 24 shows the movements of buses in the area.

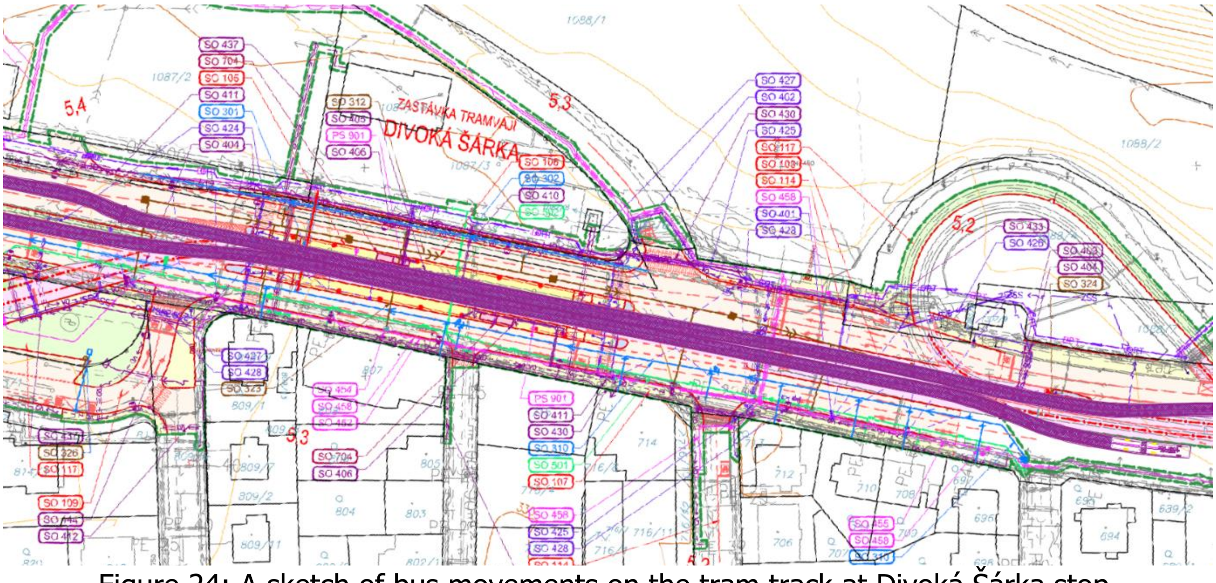

Figure 24: A sketch of bus movements on the tram track at Divoká Šárka stop.

Tramways and buses in both directions will now be using the newly constructed stop in the median of Evropská Street. The extended tramway track will be then crossing the Evropská Street and therefore the intersection Evropská X Vlastina has been redesigned. The in and out lanes of Vlastina Street have been split into two parts – Evropská at Vlastina and Evropská at Litovická. In between these segments, a tramway track is situated.

Simulation outputs

Table 8: Evaluation of delays and LOS at intersections in Model 1.

MODEL 1: 2022 TRAM EXTENSION	NODES EVALUATION [sec]			ALL TRAFFIC	CARS	TRAM ROUTE 20	BUS ROUTE 119	BUS ROUTE 300
	intersection							
	1	Evr. at Veleslav.	Delay	28,77	27,85	19,12	62,95	64,62
			LOS	C	C	B	E	E
	2	Evr. at garáže MV	Delay	15,41	15,50	16,47	12,53	10,17
			LOS	B	B	B	B	B
	3	Evr. at Do Vozovny	Delay	10,53	10,38	16,47	10,14	10,19
			LOS	B	B	B	B	B
	4	Evr. at Libocká	Delay	8,45	8,00	13,78	19,24	18,15
			LOS	A	A	B	C	C
	5	Evr. at Vlastina	Delay	14,32	13,77	21,14	32,43	15,54
			LOS	B	B	C	C	B

The challenge for the overall traffic on Evropská is the newly redesigned intersection Evropská at Vlastina. Especially the eastbound lanes of Evropská could be potentially affected by the tramway crossing. However, according to outputs, this redesign does not make significant change to the current traffic as the levels of service and delays remained the same. As for the public transit, it is difficult to compare LOS with current design as the newly constructed tram stop is placed directly at the stop line of the intersection, which can affect the results. Generally, the new organization of this node introduces higher level of physical segregation of transit vehicles from other traffic as the buses drive more than 200 meters on tram track. This can have positive effect in reducing delays. The other intersections have not been affected.

5.3 Model 2: 2030 with Partial Ring Road

The third model includes the extended tramway track, and the inserted volumes are based on forecasts for 2030. These forecasts do not consider the completion of Prague's Ring Road (D0). The construction works on the northern part of the Ring Road (sections 518, 519 and 520) were expected to start in 2025, but the project is yet to receive building permit which means that the start date will be postponed to 2028 at earliest. The construction itself should take 10 years, which means that in 2030 the Ring Road will most likely not be completed and thus this model will be the most accurate representation of traffic in that time. The impact of construction of the Ring Road on the volumes on Evropská will be significant. After opening the Ring Road, the flows in eastbound lanes are expected to drop by 33%, respectively by 30% in westbound lanes compared to volumes without completed Ring Road.

If we compare the forecasted volumes (scenario with Partial Ring Road) with current traffic, there will be an increase by 24% in the eastbound lanes and by 15% in the westbound lanes, according to traffic model of TSK.

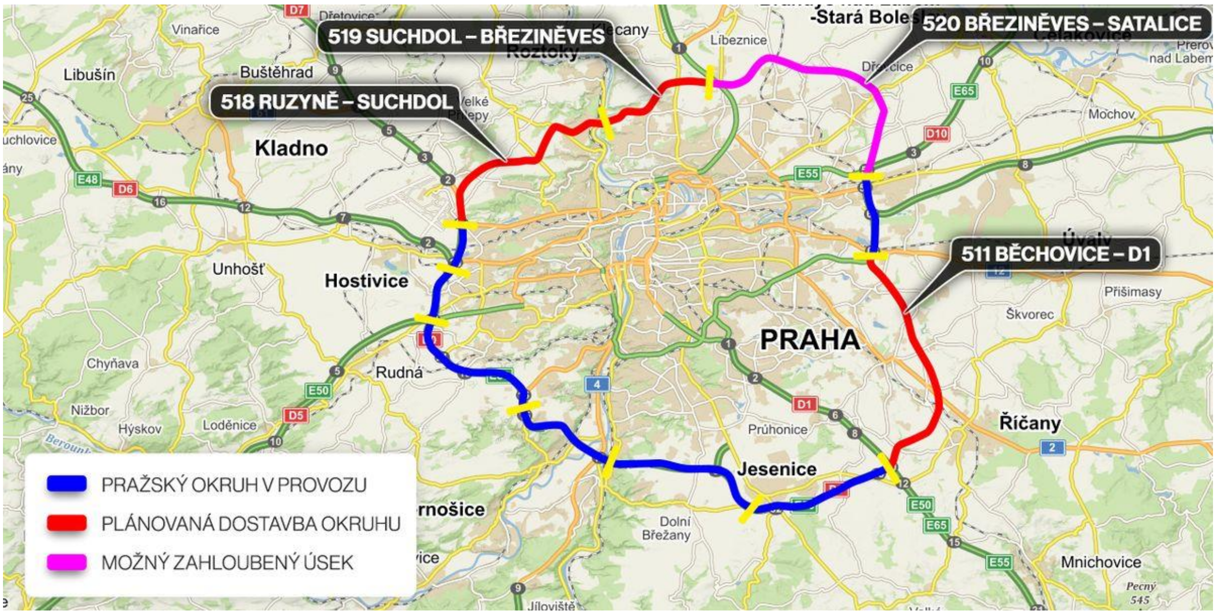

Figure 25: The plan of the construction of Prague's Ring Road (D0). BLUE = sections in operation, RED = proposed sections, PINK = proposed sections in tunnels. [novinky.cz]

Another important factor when assessing the future traffic on Evropská Street is the level of completion of the new railway to the airport. Once this service is launched, public transit in the area is going to be fundamentally reorganized. The official document "Prospects of transit routes development in 2022-2032" by PID proposes that the bus route 119 would be converted to trolleybus route 59 and rerouted to newly constructed transfer Dlouhá Míle located nearby the Airport and Ring Road [25]. Bus connections to the airport will be fully replaced by trains. Additionally, most of the regional buses will be rerouted to Dlouhá Míle transfer center and will not enter Prague. Due to these changes, buses will almost completely disappear from Evropská Street and Nádraží Veleslavín transfer center will be abandoned.

The original plans expected the railway to be opened by 2030. However, according to most recent statements of SŽ, the railway infrastructure manager, it is very unclear if the railway will be built in time and therefore this model still includes all bus routes as they are now.

Simulation outputs

Table 9: Evaluation of delays and LOS at intersections in Model 2.

MODEL 2: 2030 WITH PARTIAL RING ROAD	NODES EVALUATION [sec]			ALL TRAFFIC	CARS	TRAM ROUTE 20	BUS ROUTE 119	BUS ROUTE 300
	intersection							
	1	Evr. at Veleslav.	Delay	29,11	29,81	19,11	80,72	74,29
			LOS	C	C	B	F	E
	2	Evr. at garáže MV	Delay	16,79	16,92	16,47	13,10	12,82
			LOS	B	B	B	B	B
	3	Evr. at Do Vozovny	Delay	11,80	11,73	16,47	11,37	10,82
			LOS	B	B	B	B	B
	4	Evr. at Libocká	Delay	9,84	9,71	14,23	20,00	17,14
			LOS	B	B	B	C	B
	5	Evr. at Vlastina	Delay	15,57	15,24	21,53	32,43	17,45
			LOS	B	B	C	C	B

We can notice an increase of delays at most of the intersections as a result of higher volumes in 2030. The levels of service of cars and buses dropped by one grade at the intersection nr.1, with buses being at the lowest level of service possible (F = forced or breakdown flow).

5.4 Model 3: 2030 with Completed Ring Road

The last of the initial simulation models is based on the same network as a previous model, but with the 2030 volume forecasts that take into account the completion of Prague's Ring Road (D0). The forecasted volumes are significantly lower compared to the variant with partial Ring Road, and even compared to 2022 volumes (-13% eastbound and – 18% westbound). The Ring Road is a priority infrastructure project for Prague as it will allow the transfer of transiting traffic from the inner corridors like Evropská to the outer road network. It will also take over some part of the intra-city traffic relations, especially in the city districts adjacent to the ring road. This model represents the best-case scenario if all works on the Ring Road were done by 2030, which seems to be unlikely to happen considering the slow development so far. To be consistent with previous models, this model does not consider railway to airport either.

Simulation outputs

Table 10: Evaluation of delays and LOS at intersections in Model 3.

MODEL 3: 2030 WITH COMPLET. RING R.	NODES EVALUATION [sec]			ALL TRAFFIC	CARS	TRAM ROUTE 20	BUS ROUTE 119	BUS ROUTE 300
	intersection							
	1	Evr. at Veleslav.	Delay	27,73	26,83	19,18	54,26	36,41
			LOS	C	C	B	D	D
	2	Evr. at garáže MV	Delay	13,83	13,88	16,19	10,58	11,04
			LOS	B	B	B	B	B
	3	Evr. at Do Vozovny	Delay	8,92	8,69	16,15	6,90	2,46
			LOS	A	A	B	A	A
	4	Evr. at Libocká	Delay	7,71	7,52	10,03	18,36	13,04
			LOS	A	A	B	B	B
	5	Evr. at Vlastina	Delay	13,11	12,79	14,24	28,77	15,95
			LOS	B	B	B	C	B

When compared to previous models, this model experienced lower delays at most of the intersections thanks to overall lower volumes. The LOS of public transit routes at the first intersection has improved by one grade compared to 2022 volumes, but this places still remains the biggest bottleneck of the entire network.

5.5 Comparison of initial simulation models

To make the comparison of all initial models more transparent, a summarizing table of travel times achieved in individual models was created. The travel times were measured in two sections of Evropská Street, in both directions (EB, WB). The first section is from Nádraží Veleslavín transfer center to Divoká Šárka and the second from Divoká Šárka to Ring Road.

Table 11: Comparison of travel times achieved in initial simulation models.

TRAVEL TIMES COMPARISON [sec]		MODEL 0 2022 CURRENT STATE	MODEL 1 2022 TRAM EXTENSION	MODEL 2 2030 WITH PARTIAL RING ROAD	MODEL 3 2030 WITH COMPLETED RING ROAD
CARS	VELESLAVÍN –> ŠÁRKA (WB)	166,33	*152,01*	155,05	**144,51**
CARS	ŠÁRKA –> VELESLAVÍN (EB)	167,81	169,35	*178,84*	**160,99**
CARS	ŠÁRKA –> RING ROAD (WB)	77,14	76,33	77,50	75,56
CARS	RING ROAD –> ŠÁRKA (EB)	92,39	85,25	89,91	81,76
CARS	WHOLE EVROPSKÁ (WB)	257,32	242,50	*246,71*	**234,21**
CARS	WHOLE EVROPSKÁ (EB)	276,05	269,18	*283,40*	**257,59**
TRAM 20	VELESLAVÍN –> ŠÁRKA (WB)	199,92	201,50	202,49	199,74
TRAM 20	ŠÁRKA –> VELESLAVÍN (EB)	204,59	206,66	207,71	204,43
BUS 119	VELESLAVÍN –> ŠÁRKA (WB)	212,90	205,87	*218,21*	**194,52**
BUS 119	ŠÁRKA –> VELESLAVÍN (EB)	*208,35*	200,78	205,32	**191,94**
BUS 119	ŠÁRKA –> NAVIGÁTORŮ (WB)	160,80	162,48	*167,53*	**155,70**
BUS 119	NAVIGÁTORŮ –> ŠÁRKA (EB)	116,05	120,45	121,67	117,54
BUS 300	VELESLAVÍN –> ŠÁRKA (WB)	196,26	194,68	*205,28*	**141,47**
BUS 300	ŠÁRKA –> VELESLAVÍN (EB)	*203,19*	189,15	198,42	**166,09**
BUS 300	ŠÁRKA –> NAVIGÁTORŮ (WB)	143,89	144,15	136,96	139,98
BUS 300	NAVIGÁTORŮ –> ŠÁRKA (EB)	93,45	95,28	*101,68*	**88,76**

As expected, the best travel times were experienced in the model with completed Ring Road and the worst in the model with partial Ring Road. When comparing the current infrastructure with the models with extended tramway, it must be noted that the design and location of bus and tramway stops at Divoká Šárka has changed and therefore the comparison is inaccurate. Additionally, the travel times of bus and tramway routes were measured between stops, whereas car sections were measured between intersection. Therefore, these sections are not identical, and their comparison is misleading.

The lowest values were made bold and green, the highest are written in red italics. Cells in a row where no significant changes were achieved remained plane.

Figure 26 compares the average travel times of cars and route 119 achieved in the section from Nádraží Veleslavín to Divoká Šárka in all initial models. This is the essential section for the analysis of TSP scenarios, which will be elaborated in the next chapter.

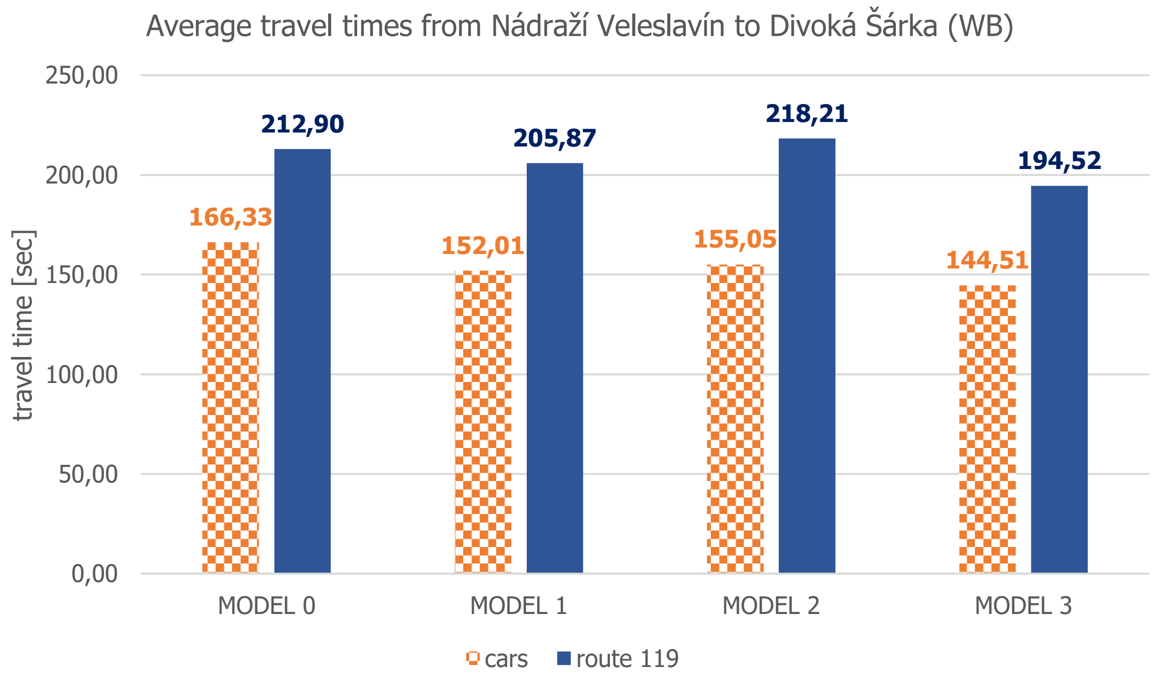

Figure 26: The comparison of average travel times of cars and route 119.

5.6 Suggested improvements

Based on the results obtained from 4 initial models, improvements to the transit signal priority system on Evropská Street were suggested.

The tramway signal priority proved to be effective and requires no modification. The biggest delays were experienced by buses leaving the Nádraží Veleslavín transfer center and therefore the main changes to the operation of buses have to be applied there. The left turning lane used by all buses leaving the transfer center is too short and frequently occupied by other types of vehicles. This needs to be fixed by extending the turning lane and restrict its utilization.

Additionally, it would be beneficial to take advantage of the possible time savings in the intersection and give buses passive priority in the following section of Evropská Street. For instance, buses heading westbound could be supported by new dedicated bus lane.

Modifications to TSP system were elaborated in three scenarios:

Scenario A: Dedicated bus turn lane on exit from Veleslavín followed by bus lane on Evropská.

Scenario B: Dedicated bus turn lane on exit from Veleslavín with a designated signal for buses followed by operation of buses on tram track.

Scenario C: Bus signal priority on exit from Veleslavín on the basis of existing design.

Models with the three suggested scenarios will be evaluated in the next chapter. Scenarios will be applied to models 1 and 2 to determine their effect within 2022 as well as 2030 volumes. The evaluation will focus on how the specific TSP measure improves operation of public transit and what impact it has on other modes of transport in comparison with existing state. This can help to identify the most important factors affecting the transit signal priority and inform decisions on which scenario improves the transit performance more.

Chapter 6: IMPROVEMENTS OF TRANSIT SIGNAL PRIORITY

6.1 Scenario A: Dedicated bus lane on exit from Nádraží Veleslavín + bus lanes

This scenario suggests a transformation of the existing left turning lane on the northbound approach into a lane dedicated exclusively for buses. Buses would use this lane and follow the existing signal plan. Bus movement in the intersection would be changed in order to use the tram track on the way downstream instead of the regular lane. After passing through the Nádraží Veleslavín tram stop, buses would merge back into to the regular lane. Cars and other traffic would use the remaining lane to do straight and turning movements.

Figure 27: Scheme of movements in the intersection when buses leave Nádraží Veleslavín.

To support the priority of buses heading westbound, a new dedicated bus lane would be applied on the left westbound lane of Evropská Street at the section from Nádraží Veleslavín to Divoká Šárka. This should help to avoid difficulties with merging back from the tram track into regular road and also ensure reducing disruptions to bus operation in case of congestions.

Described modifications would not need significant changes to the infrastructure, except for the traffic signage and markings, and the rebuilding of approximately 50 meters of grass covered tramway track to concrete.

6.2 Scenario B: Designated bus lane and signal + buses on tram track

The second scenario also proposes a transformation of the existing left turning lane on northbound approach into a dedicated bus lane. In addition to that, it suggests a creation of designated signal phase only for buses. Buses would take advantage of their own signal phase for leaving and entering the transfer center. Buses on the approach to/from the transfer center would send their request for green signal to the traffic signal controller and the signal phase for their movement would be incorporated in the signal plan.

To support the time savings made at the intersection, this scenario suggests operation of all bus routes on the tram track in the section from Divoká Šárka to Nádraží Veleslavín in both directions. Buses would stop at the existing tram stops in median (instead of regular bus stops) and the dedicated bus lane in the right eastbound lane of Evropská Street would be removed. As for traffic management at following intersections on Evropská, buses driving on the tram track would be following the same signals as trams, which would give them additional priority.

According to traffic regulations, buses are allowed to drive on the tram track if the minimal width of a tram track is 6.5 meters, which is the case of tram track on Evropská Street [26].

The drawback of this solution is the fact that the tramway track is currently covered with grass or stones and therefore a large investment would be needed for rebuilding it into concrete.

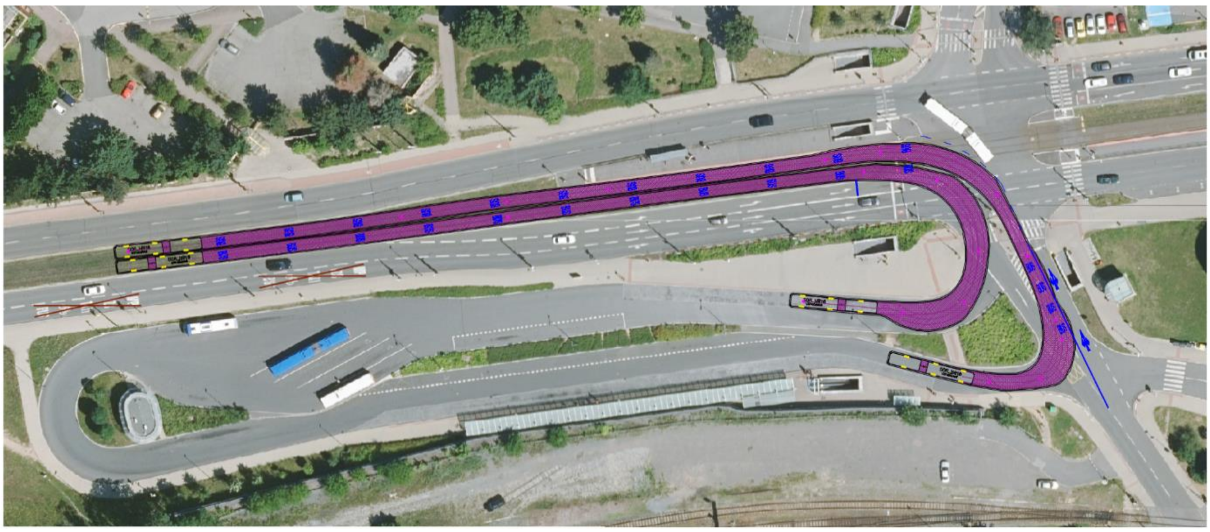

Figure 28: The scheme of bus movements during designated signal phase for buses.

6.3 Scenario C: Bus Signal Priority

The third and the last scenario is based on the current design of the intersection 1, without any changes to channelization, but with the bus signal priority implemented on the northbound approach to the intersection. Buses approaching the exit from Veleslavín would be requesting their priority via radio communication and the signal controller would shorten the red period / extend green to enable buses to pass through the intersection. Due to high volumes of colliding flows on Evropská Street, the activation of TSP has to be limited by conditions that do not allow buses to request priority too soon after one and other.

Figure 29: The scheme of movements within the bus signal priority phase.

The bus signal priority in VISSIM has been simulated in a simplified version with the help of two detectors. The check-in detector was placed at the point where buses leave the transfer center and the check-out detector at the point where buses finish their turning movement. The priority requests were limited by setting the minimal gap between activation of prioritized phases for 45 seconds.

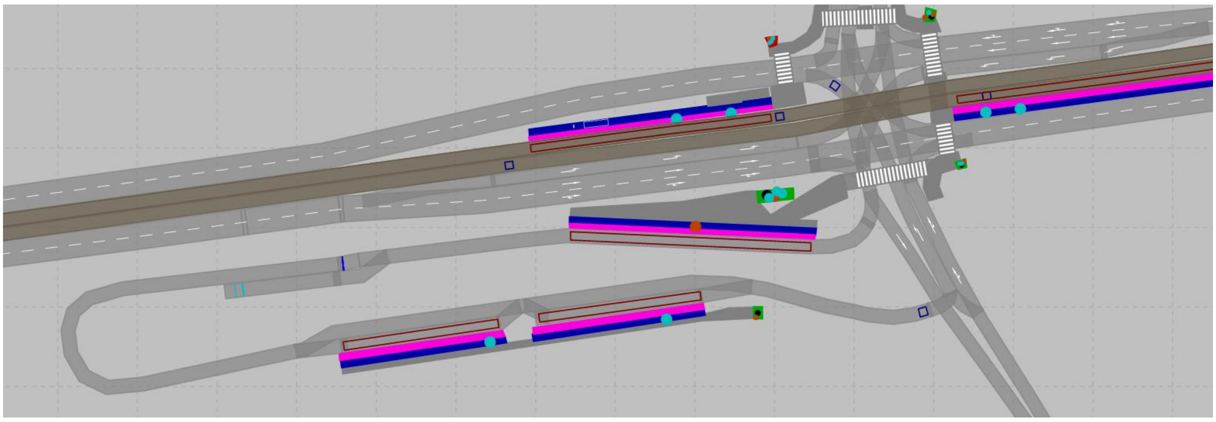

Figure 30: The screenshot showing the placement of detectors.

6.4 Comparison of suggested scenarios

Impact on intersection 1 in 2022

Firstly, the suggested scenarios were implemented to model 1, which demonstrates the conditions on Evropská Street in 2022. The outputs of the models can be found on the next pages under the names 1A, 1B and 1C (1 = initial model 1, A/B/C = TSP scenario). The following analysis of results focuses mainly on bus route 119 in section Veleslavín – Šárka.

The results showed that all three proposed TSP scenarios are capable of reducing the average delays of bus routes at the intersection 1, which results in their improved Level of Service (D). Compared to the current state without any bus priority, the new TSP scenarios reduced the average delay of route 119 at intersection 1 by approximately 10 seconds – 16% (model 1A), 12 seconds – 19% (1C), respectively by 20 seconds (32%) in case of model 1B.

A bigger difference between the scenarios is in the impact on other vehicle types. Whereas the scenario A managed to keep the delay of cars at the same level, because no changes to the signal plan were made, scenario B with its designated signal phase increased the delay of cars by 16 seconds (57%). The scenario C increased the delay of cars by 10 seconds (35%).

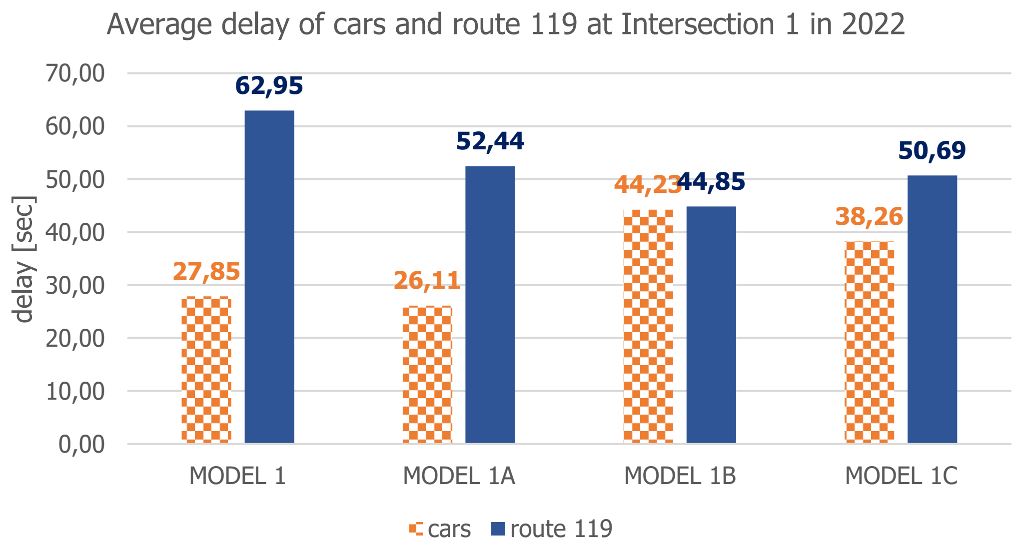

Figure 31: Average delays of cars and route 119 at intersection 1 in 2022.

Table 12: Evaluation of delays and LOS at intersections in Model 1A.

MODEL 1A: 2022 BUS LANES	NODES EVALUATION [sec]			ALL TRAFFIC	CARS	TRAM ROUTE 20	BUS ROUTE 119	BUS ROUTE 300
	intersection							
	1	Evr. at Veleslav.	Delay	26,82	26,11	19,04	52,44	41,75
			LOS	C	C	B	D	D
	2	Evr. at garáže MV	Delay	14,72	14,83	16,19	10,01	9,16
			LOS	B	B	B	B	A
	3	Evr. at Do Vozovny	Delay	9,54	9,39	16,15	6,74	7,64
			LOS	A	A	B	A	A
	4	Evr. at Libocká	Delay	7,45	7,08	11,04	17,71	12,68
			LOS	A	A	B	B	B
	5	Evr. at Vlastina	Delay	13,62	13,04	14,84	29,74	13,84
			LOS	B	B	B	C	B

Table 13: Evaluation of delays and LOS at intersections in Model 1B.

MODEL 1B: 2022 BUSES ON TRAM TRACK	NODES EVALUATION [sec]			ALL TRAFFIC	CARS	TRAM ROUTE 20	BUS ROUTE 119	BUS ROUTE 300
	intersection							
	1	Evr. at Veleslav.	Delay	44,34	44,23	43,62	44,85	45,74
			LOS	D	D	D	D	D
	2	Evr. at garáže MV	Delay	14,48	13,95	16,44	30,65	24,90
			LOS	B	B	B	C	C
	3	Evr. at Do Vozovny	Delay	9,98	9,95	16,54	6,04	8,81
			LOS	B	B	B	A	B
	4	Evr. at Libocká	Delay	8,37	7,87	12,62	25,36	18,18
			LOS	A	A	B	C	B
	5	Evr. at Vlastina	Delay	16,98	16,58	15,09	30,31	15,07
			LOS	B	B	B	C	B

Table 14: Evaluation of delays and LOS at intersections in Model 1C.

MODEL 1C: 2022 BUS SIGNAL PRIORITY	NODES EVALUATION [sec]			ALL TRAFFIC	CARS	TRAM ROUTE 20	BUS ROUTE 119	BUS ROUTE 300
	intersection							
	1	Evr. at Veleslav.	Delay	38,63	38,26	19,23	50,69	46,45
			LOS	D	D	B	D	D
	2	Evr. at garáže MV	Delay	14,88	14,90	16,35	11,92	12,02
			LOS	B	B	B	B	B
	3	Evr. at Do Vozovny	Delay	10,26	10,08	16,32	10,95	8,54
			LOS	A	A	B	B	A
	4	Evr. at Libocká	Delay	7,98	7,63	10,78	19,37	15,03
			LOS	A	A	B	B	B
	5	Evr. at Vlastina	Delay	14,74	14,26	14,67	32,27	17,01
			LOS	B	B	B	C	B

Comparison of travel times in 2022

If we have a look at average travel times of public transit achieved in individual models, we can compare how much of time savings can be achieved with different scenarios.

Even though the scenario B proved to be the most effective in prioritizing the public transit at intersection 1, the average time savings on route 119 in section from Veleslavín to Divoká Šárka were only 20 seconds (10%). That was caused mainly by the fact that buses driving on the tram track were often blocked by tramways and other bus routes servicing stops on Evropská Street, which are not regularly serviced by this route. Therefore, the travel time savings were not so significant. The biggest time savings were achieved with scenario C, which saved almost 40 seconds (20%) of travel time in this section. The scenario A saved just 5 seconds, which was expected because there was no intervention incorporated into signal plan.

As for the eastbound, the only time savings were seen in scenario B. On the contrary, scenario C increased the travel time of route 119 in direction to Nádraží Veleslavín by 5 seconds.

In the Figure 32, you can see how various TSP scenarios affected travel times of cars driving westbound. The only scenario with positive impact on cars in westbound lanes was scenario B because it did not interfere this lane and shifted buses from the tram track. Scenario C increased the average travel times of cars by approximately 10 seconds in both directions.

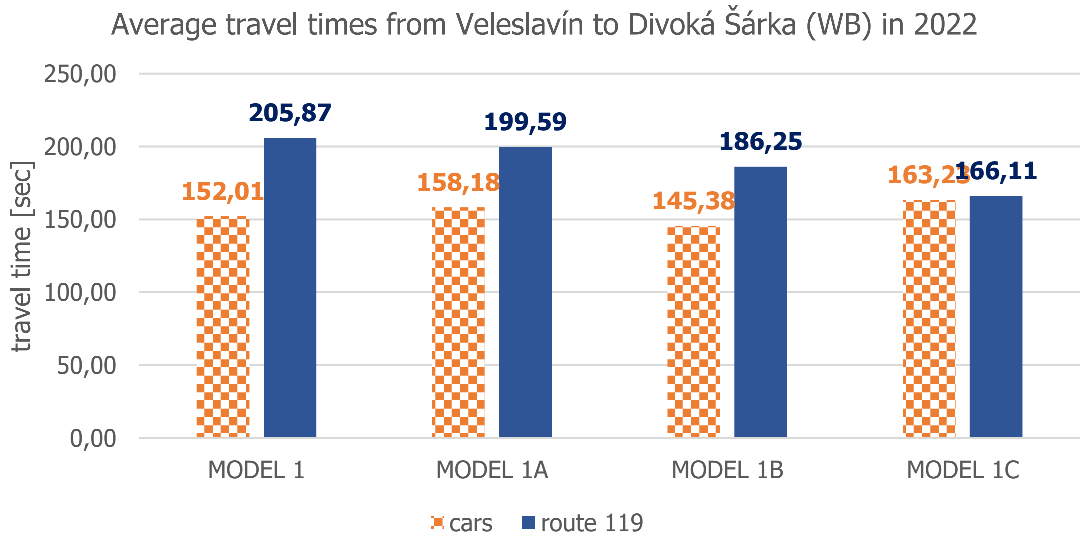

Figure 32: Average travel times of cars and route 119 achieved on Evropská Street in 2022.

Table 15: The comparison of travel times achieved in 2022 with different TSP scenarios.

TRAVEL TIMES COMPARISON [sec]		MODEL 1 2022 TRAM EXTENSION	MODEL 1A 2022 BUS LANES	MODEL 1B 2022 BUSES ON TRAM TRACK	MODEL 1C 2022 BUS SIGNAL PRIORITY
CARS	VELESLAVÍN –> ŠÁRKA (WB)	152,01	158,18	**145,38**	*163,23*
CARS	ŠÁRKA –> VELESLAVÍN (EB)	169,35	**168,86**	178,12	*181,31*
CARS	ŠÁRKA –> RING ROAD (WB)	76,33	76,60	76,96	76,61
CARS	RING ROAD –> ŠÁRKA (EB)	85,25	84,83	84,41	84,57
CARS	WHOLE EVROPSKÁ (WB)	242,50	248,79	**236,59**	*255,95*
CARS	WHOLE EVROPSKÁ (EB)	269,18	**268,21**	277,81	*280,80*
TRAM 20	VELESLAVÍN –> ŠÁRKA (WB)	201,50	201,68	*212,57*	202,07
TRAM 20	ŠÁRKA –> VELESLAVÍN (EB)	206,66	208,40	*221,13*	205,59
BUS 119	VELESLAVÍN –> ŠÁRKA (WB)	*205,87*	199,59	186,25	**166,11**
BUS 119	ŠÁRKA –> VELESLAVÍN (EB)	200,78	196,15	**183,34**	*205,65*
BUS 119	ŠÁRKA –> NAVIGÁTORŮ (WB)	162,48	168,41	162,03	161,57
BUS 119	NAVIGÁTORŮ –> ŠÁRKA (EB)	120,45	119,66	119,89	118,33
BUS 300	VELESLAVÍN –> ŠÁRKA (WB)	*194,68*	178,94	172,29	**146,71**
BUS 300	ŠÁRKA –> VELESLAVÍN (EB)	189,15	194,55	**175,76**	*204,82*
BUS 300	ŠÁRKA –> NAVIGÁTORŮ (WB)	144,15	139,41	145,13	139,57
BUS 300	NAVIGÁTORŮ –> ŠÁRKA (EB)	95,28	97,83	92,20	97,12

Impact on intersection 1 in 2030

In the next part, all three scenarios were applied into model 2, which represents the worst-case projections for 2030. The results experienced in models 2A, 2B and 2C proved the findings from the analysis of 2022 volumes.

The average delays of public transit at intersection 1 were reduced by all three TSP scenarios. The biggest improvements were seen in scenario B, which reduced the delay of bus route 119 by 30 seconds (38%), followed by scenario C (29 seconds – 36%) and scenario A (23 seconds – 29%). The LOS has improved by two grades in scenarios B and C, and by one grade is scenario A.

When compared to the results from 2022, the relative reductions of delay in all scenarios are significantly higher. That means that the bigger the volumes, the bigger are savings by TSP.

The most negative impact on the other traffic had again the scenario B, which increased the average delay of cars at the intersection by 17 seconds (36%). Scenario C increased the delay of cars by 12 seconds (28%), and scenario A only by 2 seconds.

Figure 33 shows how the average delays of cars and route 119 at intersection 1 changes within different scenarios.

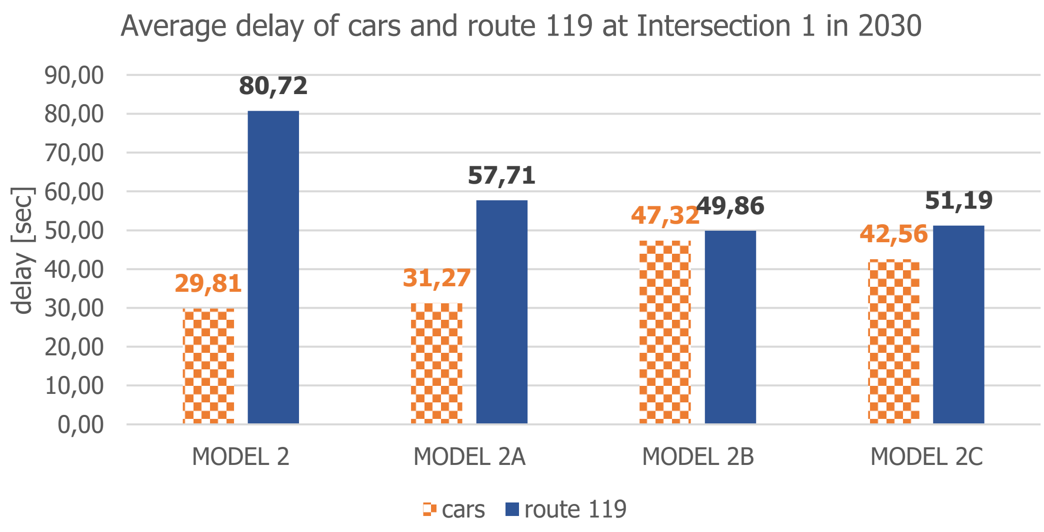

Figure 33: Average delays of cars and route 119 at intersection 1 in 2030.

Table 16: Evaluation of delay and LOS at intersections in Model 2A.

MODEL 2A: 2030 BUS LANES	NODES EVALUATION [sec]			ALL TRAFFIC	CARS	TRAM ROUTE 20	BUS ROUTE 119	BUS ROUTE 300
	intersection							
	1	Evr. at Veleslav.	Delay	31,99	31,27	19,42	57,71	54,97
			LOS	C	C	B	E	E
	2	Evr. at garáže MV	Delay	15,64	15,68	16,31	13,99	17,77
			LOS	B	B	B	B	B
	3	Evr. at Do Vozovny	Delay	13,20	13,36	16,27	10,13	8,74
			LOS	B	B	B	B	A
	4	Evr. at Libocká	Delay	9,26	9,11	10,67	20,73	15,65
			LOS	A	A	B	V	B
	5	Evr. at Vlastina	Delay	15,14	14,80	14,74	35,21	18,06
			LOS	B	B	B	D	B

Table 17: Evaluation of delay and LOS at intersections in Model 2B.

MODEL 2B: 2030 BUSES ON TRAM TRACK	NODES EVALUATION [sec]			ALL TRAFFIC	CARS	TRAM ROUTE 20	BUS ROUTE 119	BUS ROUTE 300
	intersection							
	1	Evr. at Veleslav.	Delay	47,62	47,32	48,23	49,86	49,61
			LOS	D	D	D	D	D
	2	Evr. at garáže MV	Delay	15,01	14,52	16,16	28,77	23,91
			LOS	B	B	B	C	C
	3	Evr. at Do Vozovny	Delay	8,82	8,72	16,15	4,88	8,60
			LOS	A	A	B	A	A
	4	Evr. at Libocká	Delay	9,64	9,48	11,59	24,96	10,60
			LOS	A	A	B	C	B
	5	Evr. at Vlastina	Delay	17,64	17,28	14,47	30,34	17,28
			LOS	B	B	B	C	B

Table 18: Evaluation of delays and LOS at intersections in Model 2C.

MODEL 2C: 2030 BUS SIGNAL PRIORITY	NODES EVALUATION [sec]			ALL TRAFFIC	CARS	TRAM ROUTE 20	BUS ROUTE 119	BUS ROUTE 300
	intersection							
	1	Evr. at Veleslav.	Delay	42,94	42,56	18,98	51,19	45,97
			LOS	D	D	B	D	D
	2	Evr. at garáže MV	Delay	15,21	15,26	16,19	11,84	15,18
			LOS	B	B	B	B	B
	3	Evr. at Do Vozovny	Delay	10,70	10,61	16,15	8,22	6,62
			LOS	B	B	B	A	A
	4	Evr. at Libocká	Delay	8,82	8,59	10,34	20,18	15,16
			LOS	A	A	B	C	B
	5	Evr. at Vlastina	Delay	14,91	14,54	14,42	31,31	14,87
			LOS	B	B	B	C	B

Comparison of travel times in 2030

If we compare the impact of the three suggested scenarios on the travel times in 2030, we can observe that the savings achieved in 2030 are proportionally same to the savings achieved in 2022. The biggest savings in travel time of route 119 in direction to the airport are achieved when scenario C is implemented (50 seconds – 22%), followed by scenario B (25 seconds – 12%), ands scenario A, which only saved approximately 12 seconds (5%).

As for the eastbound, only scenario B can reduce travel times of route 119 in this direction, but only at the expanse of cars in this direction (+40 seconds). Generally, operation of buses on tram track on Evropská Street has not proved to be beneficial as the achieved savings were not as big compared to scenario C. Moreover, the travel times of tramway 20 also showed increase within scenario B, which means that buses and tramways were hindering each other.

Scenario C increased the average travel times of traffic going both eastbound and westbound by approximately 20 seconds and made the travel times of buses in section Veleslavín – Šárka comparable with travel times of cars. Figure 34 shows travel times on Evropská in 2030.

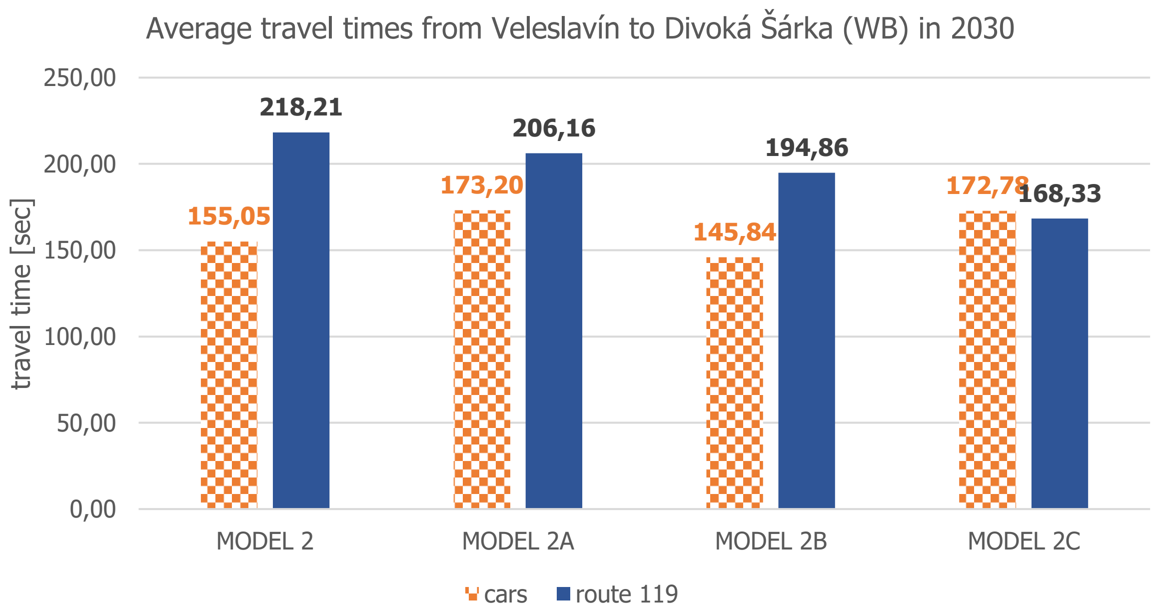

Figure 34: Average travel times of cars and route 119 achieved on Evropská Street in 2030.

Table 19: The comparison of travel times achieved in 2030 with different TSP scenarios.

TRAVEL TIMES COMPARISON [sec]		MODEL 2 2030 WITH PARTIAL RING ROAD	MODEL 2A 2030 BUS LANES	MODEL 2B 2030 BUSES ON TRAM TRACK	MODEL 2C 2030 BUS SIGNAL PRIORITY
CARS	VELESLAVÍN –> ŠÁRKA (WB)	155,05	*173,20*	**145,84**	172,78
CARS	ŠÁRKA –> VELESLAVÍN (EB)	178,84	**175,69**	*219,51*	203,40
CARS	ŠÁRKA –> RING ROAD (WB)	77,50	99,15	76,32	77,44
CARS	RING ROAD –> ŠÁRKA (EB)	89,91	109,32	88,08	89,13
CARS	WHOLE EVROPSKÁ (WB)	246,71	*286,54*	**235,87**	270,48
CARS	WHOLE EVROPSKÁ (EB)	**283,40**	299,22	*323,47*	306,70
TRAM 20	VELESLAVÍN –> ŠÁRKA (WB)	202,49	201,18	*212,30*	201,12
TRAM 20	ŠÁRKA –> VELESLAVÍN (EB)	207,71	206,99	*243,48*	207,00
BUS 119	VELESLAVÍN –> ŠÁRKA (WB)	*218,21*	206,16	194,86	**168,33**
BUS 119	ŠÁRKA –> VELESLAVÍN (EB)	205,32	203,28	**189,41**	*213,66*
BUS 119	ŠÁRKA –> NAVIGÁTORŮ (WB)	167,53	221,52	179,29	168,32
BUS 119	NAVIGÁTORŮ –> ŠÁRKA (EB)	121,67	173,00	120,30	121,49
BUS 300	VELESLAVÍN –> ŠÁRKA (WB)	*205,28*	191,16	194,35	**148,78**
BUS 300	ŠÁRKA –> VELESLAVÍN (EB)	*198,42*	184,59	**171,18**	193,51
BUS 300	ŠÁRKA –> NAVIGÁTORŮ (WB)	136,96	226,95	141,30	142,39
BUS 300	NAVIGÁTORŮ –> ŠÁRKA (EB)	101,68	158,52	91,56	100,02

Chapter 7: CONCLUSION

7.1 Summary of Findings

This thesis was dedicated to the topic of transit signal priority (TSP) on Evropská Street in Prague. After the literature review of TSP strategies and implementations, the current traffic conditions on Evropská Street were examined. This research has developed microscopic traffic simulation models of the 3.5 km long section of Evropská Street between Nádraží Veleslavín transfer center and Prague's Outer Ring Road. Based on the results of the simulation, the bottlenecks on the infrastructure were identified and three scenarios to improve the bus on-time performance were suggested. The suggested scenarios were implemented in the models with 2022 as well as 2030 volumes and the possible travel time savings of bus routes were calculated. The biggest potential travel time savings were achieved by implementing bus signal priority (scenario C) on the northbound approach of the intersection 1 (6.120 Evropská at Veleslavínská). The travel time savings achieved on the most frequent bus route 119 in the westbound section Nádraží Veleslavín – Divoká Šárka were approximately of 40 seconds in 2022 (20%), respectively 50 seconds (22%) in 2030.

7.2 Contribution

The findings from this research could be beneficial mainly for the transit agency responsible for providing public transit in the area. The travel time savings could have positive impact not only for public transit passengers, but also for the transit operator as it could save expenses on fuel for buses queuing at the intersection, and potentially even reduce the number of dispatched vehicles.

7.3 Challenges

There were a few constraints encountered during the research. The main limitation was the fact that the dynamic signal control is implemented at all intersections on Evropská Street and this kind of complex programming algorithm-based control is hard to replicate in VISSIM. The simplified version based on fixed-time control was simulated instead. Additionally, the transit signal priority was also modelled in its simplified version using a pair of detectors placed upstream and downstream of the intersection, whereas in real-world conditions the GPS-based active detection of transit vehicles is employed. The logic of giving priority to transit vehicles is also a lot more complicated as is based on detailed set of conditions reflecting the delay of transit vehicles and the actual volumes of colliding traffic flows.

7.4 Recommendations

Based on the simulation outputs, the biggest bottleneck on the infrastructure from the perspective of public transit operation is the exit from Nádraží Veleslavín transfer center. The left turning lane on the northbound approach of the intersection 1 (6.120 Evropská at Veleslavínská) is too short and frequently occupied by cars, which makes the exit of buses from the transfer center difficult. The left turning lane should be extended and preferably transformed into a dedicated bus lane as suggested in scenario A. Considering the fact that new 24-meters long bi-articulated trolleybuses are going to be dispatched on route 119, this is essential for ensuring safe exit from the transfer center.

The best time savings of bus routes heading westbound were achieved with implementation of bus signal priority (scenario C) at intersection 1. At the same time, this measure delayed the cars making straight movement on Evropská Street. The final decision would have to therefore be a consensus between transit agency, infrastructure manager and the municipality. Only conditional priority would be acceptable for this kind of intersection. The negative impact on other traffic on Evropská Street would have to be minimized by specifying precise conditions on when the priority is activated. The priority could be restricted for example only to particular routes.

The application of dedicated bus lane in the westbound left lane of Evropská Street in section Nádraží Veleslavín – Divoká Šárka has not proved to cause any significant changes for cars, nor benefits for public transit vehicles. This applies in case when no extraordinary event happens, and no congestions occur. Otherwise, bus lanes might become effective in improving reliability and on-time performance of buses as well as in allowing emergency vehicles or taxis to cut through the traffic.

The operation of buses on tram track in Scenario B has not experienced sufficient time savings (compared to scenario C) to justify the investments into reconstructions of the tram track. The problem of this solution is mutual interference of buses and trams due to different stops serviced by each route.

Finally, the investments into any kind of TSP measures would have to be analyzed with regard to the planned project of railway to the airport, which would significantly reduce the number of bus routes operating on Nádraží Veslavín and Evropská Street.

7.5 Suggestions for future research

This research focused on the 3.5 km long section of Evropská street, but the simulation model could be extended to incorporate the whole length of Evropská Street even with Vítězné náměstí. This would allow to evaluate the impact of TSP on traffic in a broader context of Prague 6.

The future research on TSP could focus on evaluating how much money and emissions it can save and what influence it has on potential increased ridership.

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Glossary

ADT	Average Daily Traffic
DPP	Dopravní podnik hl. města Prahy (city-owned transport operator in Prague)
FHWA	Federal Highway Administration
HCM	Highway Capacity Manual
HGW	High Gross Weight (trucks)
LOS	Level of Service
PID	Pražská integrovaná doprava (Prague Integrated Transport system)
PTV	Planung Transport Verkehr AG (German software company)
ROPID	Regionální organizátor Pražské integrované dopravy (ROPID, transit agency)
TSK	Technická správa komunikací (city-owned road maintenance)
TSP	Transit Signal Priority

Vita

Tomáš Míča was born in 1997 in Pardubice, the Czech Republic. He graduated from the Faculty of Transportation Sciences at Czech Technical University in Prague (CTU) in 2020. His Bachelor's study program was Technology in Transportation and Telecommunications with a specialization in Transportation Systems. His bachelor thesis focused on "Long-distance bus service operation in Prague".

In 2020, he enrolled in the Dual Master's Degrees Program in Smart Cities that is based on a collaboration between CTU and The University of Texas at El Paso (UTEP). After finishing the first year at CTU, he continued with his studies at UTEP.