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YILDIZ TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF SCIENCE AND ENGINEERING

ENHANCING URBAN TRAM EFFICIENCY THROUGH TRANSIT SIGNAL PRIORITY: A CASE STUDY IN ISTANBUL

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Husamalden M.A.Alhassan

Signature

Dedicated to my family

and my best friend

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Husamalden M.A. ALHASSAN

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LIST OF ABBREVIATIONS

CO	Carbon Monoxide
EU	European Union
IBB	Istanbul Metropolitan Municipality
IETT	Istanbul Electricity, Tramway and Tunnel General Management
ITS	Intelligent Transportation Systems
LOS	Level of Service
NOx	Nitrogen Oxides
PT	Public Transport
SCATS	Sydney Coordinated Adaptive Traffic System
SCOOT	Split Cycle Offset Optimization Technique
TCQSM	Transit Capacity and Quality of Service Manual
TSP	Transit Signal Priority
US	United States
VAP	Vehicle Actuated Programming (used in VISSIM as VISVAP)
VISSIM	Verkehrs In Städten – SIMulationsmodell (PTV traffic simulation software)
VOCs	Volatile Organic Compounds

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ABSTRACT

Enhancing Urban Tram Efficiency Through Transit Signal Priority: A Case Study in Istanbul

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Master of Science Thesis

Supervisor: Assoc. Prof. Güzin AKYILDIZ ALÇURA

This study evaluates the application of TSP strategies (green extension technique) at Turgut Özal Millet Cd in Istanbul, Türkiye, a busy intersection that involves intense pedestrian, vehicular, and public transport movements, and which involves the T1 tram line and 38 bus lines. The study intends to evaluate the existing traffic conditions (base model), develop TSP scenarios, and recommend the best solution to improve tram performance with minimal effect on other road users. PTV VISSIM and VISVAP software simulations were used over three periods (8:00–9:00 a.m., 12:00–1:00 p.m., 5:00–6:00 p.m.) to compare a base model (without TSP) to a proposed scenario with green extension strategies. Overall results show significant tram improvements, tram delays reduced by 63.81–69.95% (from 14.46–16.09 s to 5.23–4.48 s), and the level of service improved from C/B to A. Network-wide, fuel consumption dropped by 1.02% (from 65.34 to 64.67 gallons), with tram-specific reductions up to 20.82%. While the person delays decreased considerably by 27.08% through the strategy, benefiting from the high capacity of the tram. On the other hand, some vehicle movements faced increased delays at intersections. Left-turn queues specifically increased by 5.98% as priority was given to the opposite direction. The strategy performs best during the evening peak,

with a person delay reduction of 42.49%. The research recommends using adaptive signal timing and conducting real-world pilots to enhance scalability and decrease vehicle delays, thus supporting sustainable urban transportation. These results provide evidence for transportation planners to support the implementation of TSP and the potential for balancing tram efficiency with mixed traffic dynamics.

Keywords: Tram signal priority, urban mobility, traffic simulation, VISSIM, TSP strategy.

ÖZET

Kentsel Tramvay Verimliliğini Transit Sinyal Önceliği ile Artırma: İstanbul'da Bir Vaka Çalışması

Husamalden Mohamed Abdalhameed ALHASSAN

İnşaat Mühendisliği Anabilim Dalı

Yüksek Lisans Tezi

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Bu çalışma, Transit Sinyal Önceliği-Transit Signal Priority (TSP) stratejilerden biri olan yeşil sürenin uzatılması yönteminin yoğun yaya, araç ve toplu taşıma hareketlerinin yer aldığı bir kavşakta uygulanmasına ilişkin değerlendirmeleri içermektedir. İncelene kavşak, T1 tramvay hattı ile 38 otobüs hattının geçtiği Turgut Özal Millet Caddesinde (İstanbul), Çapa tramvay durağının hemen öncesindeki sinyalize kavşaktır. Çalışma, mevcut trafik koşullarını (Temel model) değerlendirmeyi, TSP senaryoları geliştirmeyi ve tramvay performansını iyileştirmek için diğer yol kullanıcılarına minimum şekilde etki edecek en iyi çözümü önermeyi amaçlamaktadır. PTV VISSIM ve VISVAP yazılım simülasyonları kullanılarak üç farklı zaman aralığında (08:00-09:00, 12:00-13:00, 17:00-18:00) biri Temel Model (TSP olmadan) diğeri ise yeşil uzatma stratejileri içeren Önerilen Model (TSP ile) olmak üzere iki senaryonun karşılaştırılmasını içermektedir. Genel sonuçlar, tramvaylarda önemli iyileşmeler gösterimiştir. Tramvay gecikmeleri %63,81-69,95 oranında azalırken (14,46-16,09 saniyeden 5,23-4,48 saniyeye), hizmet seviyesi C/B'den A'ya yükselmiştir. Ağ genelinde yakıt tüketimi %1,02 azalmış (65,34 galondan 64,67 galona), tramvay özelinde ise yakıt tüketimi %20,82'ye kadar düşüş göstermiştir. Önerilen stratejiyle kişi gecikmeleri tramvayın yüksek kapasitesi sayesinde önemli ölçüde (%27,08

oranında) azalmıştır.. Öte yandan, bazı araç hareketleri kavşaklarda artan gecikmelerle karşılaşmıştır. Özellikle sola dönüş şeridinde oluşan motorlu taşıt kuyrukları, tramvaya öncelik verilmesi nedeniyle %5,98 oranında artış göstermiştir. İncelenen strateji, en iyi performansı akşam saatlerinde göstererek kişisel bazda gecikmeleri %42,49 oranında azaltmıştır. Araştırma sonuçlarına göre, transit öncelikli sinyal zamanlamasının kullanılması ve pilot uygulamalarının yapılmasıyla ölçeklenebilirliğin artırılması önerilmekte, bu sayede azalan gecikmelerin sürdürülebilir kentsel taşımacılığı desteklemesi öngörülmektedir. Bu sonuçlar, ulaşım planlayıcılarına TSP'nin uygulanması ile tramvay verimliliği ile karışık trafik dinamikleri arasındaki dengenin sahip olduğu potansiyele ilişkin kanıt sunmaktadır.

Anahtar Kelimeler: Tramvay sinyal önceliği, kentsel hareketlilik, trafik simülasyonu, VISSIM, TSP stratejisi.

1
INTRODUCTION

1.1 Background

Transportation has played an important role in promoting trade, conquest, and social communication. But it requires a significant investment of time and resources (Garber & Hoel, 2009). Transportation is a cornerstone of economic growth, urban development, and national security. So, it deserves its place as an important priority for governments worldwide. In the United States, the Department of Transportation (DOT) is focused on enhancing safety and modernizing infrastructure. Also, by promoting innovation to aid the nation's transportation networks (Federal Highway Administration, n.d.; US Department of Transportation, n.d.). In the European Union, transport policy highlights the necessity of efficient, safe, and sustainable travel. This highlights the importance that transit plays in development and regional connectivity. Through a significant investment in infrastructure and programs that encourage green and digital growth, the EU stresses the essential role of transport in improving economic resilience and connectivity. (*Safe and Sustainable Transport | European Union*, n.d.). Türkiye places high significance on the development of transportation infrastructure. This reflects its awareness of its vital role in economic growth and regional relations. The Ministry of Transport and Infrastructure rapidly invests in several areas, including roads, railways, and navigation, thereby enhancing the country's logistical capabilities. Between 1986 and 2023, Türkiye signed contracts for 270 public-private partnership projects with a total value of 204 billion US dollars to achieve this (*Infrastructure - Invest in Türkiye*, n.d.).

These actions reflect the attention assigned by governments to building sustainable transportation networks. Recognizing its importance in preserving long-term economic stability and enhancing the general quality of life for individuals.

In recent years, the growing population levels combined with low-density growth outside urban centers have created an enormous demand for transportation networks in many urban regions. Building more infrastructure to meet increasing demand is expensive, time-consuming, and often leads to increased travel.(Barton-Aschman Associates, Inc. et al., 1999). As a result, interest in enhancing Public Transport (PT) services has grown in recent decades due to rising traffic congestion, which is often accompanied by a higher incidence rate, increased fuel consumption, and higher air pollution levels. With the development of PT travel times and reliability, the goal is to attract more PT passengers to reduce the growing rate of automobile users (Marangon, 2018). Many strategies have been developed to improve the quality and reliability of public transportation, one of the most important of which is Transit Signal Priority (TSP).

Transit Signal Priority (TSP) is a control strategy that has been increasingly employed to improve transit operations in metropolitan networks. The size of the advantage achieved differs among networks regarding their operational and transit characteristics. Several studies have demonstrated that the application of TSP techniques can have an impact on decreased waiting times for priority transit vehicles and cars that go in the same direction but can have negative consequences on the delays of vehicles using the same intersection. The amount of this negative influence varies from modest increases in their delays to considerable ones, especially when the intersections operate near to saturation(Skabardonis & Christofa, 2011).

The creation of an excellent urban public transportation system may limit the amount of traffic jams and improve the road traffic conditions. Compared to buses, trams powered by electricity provide extraordinary opportunities for reducing prices and have been increasingly developed in recent years. Currently, most trams are equipped with the exclusive right of way on road sections to reduce interference from other vehicles(Naznin et al., 2017).

1.2 Literature Review

This part will present a literature review about intelligent transportation systems (ITS), transit signal priority (TSP) types, and service quality indicators like level of service (LOS). It will also discuss the theoretical knowledge under tram signal priority, gaps in previous research based on trams, and reasons for its impact on urban mobility.

1.2.1 Intelligent Transportation System

The expanding desire for mobility has overflooded major cities with automobiles, resulting in increased traffic congestion, accompanied by unpredictable problems and accidents. These figures highlight substantial inefficiencies associated with transportation, which demand the creation of technologies for more efficient and safer travel. A method to explore this is to apply the recent results in the domain of communications to the subject of transportation management (Dimitrakopoulos & Demestichas, 2010). New approaches and applications for traffic management were made possible by technological advancements, especially in computer science and communication networks. These new applications are referred to as ITS, and they are the subject of intense discussion and research by both governmental and scientific communities(Alam et al., 2016). The U.S. Department of Transportation describes ITS as systems that improve transportation safety and mobility by integrating modern communication technology into vehicles and infrastructure(*ITS - ITS Fast Facts*, n.d.). The first ITS idea was suggested by the United States (US) in the 20th century; nevertheless, it is presently a subject of intense research and development globally, notably in the US, Japan, and the European Union (EU) (An et al., 2011). ITS is based on the rising needs of transportation development. It merges information, communications, computers, and other technology and applies them in the sphere of transportation to develop an integrated system of people, roads, and vehicles by employing modern data communication technologies. It can construct a huge, full-functioning, real-time, accurate, and efficient transportation management system. ITS makes the service objects' attention transition from road managers to road users. In order to achieve this aim, ITS uses modern technology to offer drivers with road information and easy services to minimize traffic congestion and to improve road capacity (Qureshi & Abdullah, 2013).

1.2.1.1 ITS Architecture

Based on the U.S. ITS Architecture, which provides a structured framework for intelligent transportation systems, it has a multi-layered design, as shown in the Figure 1.1 Consisting of:

- Physical layer: It is the first basic layer, which includes physical devices such as sensors, traffic lights, vehicle sensors, and roadside units. It records current situation data related to traffic, such as the number of vehicles and tram arrival times, so that systems like TSP can perceive and deal with the intersection with traffic.
- Communication layer: The communication layer allows confidentiality, safety, and reliable data exchange between physical components, vehicles, and control centers. Wireless networks, vehicle-to-infrastructure (V2I) communications, etc., are used for signal priority activation, as tram detection signals are immediately transmitted to a traffic controller.
- Operation layer: Data is handled to control the operation of the traffic network. It covers the entire operational process, including the control system (the algorithms used and the way the controls), and considering algorithms for the functioning of control systems such as those implemented in PTV VISSIM for the analysis of the behavior of traffic and strategies such as green extension for the optimization of flow and minimization of signalized intersection delay.
- Service layer: Focused on end-user applications, this layer delivers services to drivers, passengers, and planners. It provides real-time traffic information, transit schedules, and performance metrics (e.g., Level of Service), enhancing user experience and supporting policy decisions for sustainable urban mobility.

This four-layer design assures connections, operation, and service. All these levels work together to achieve the intended aims.

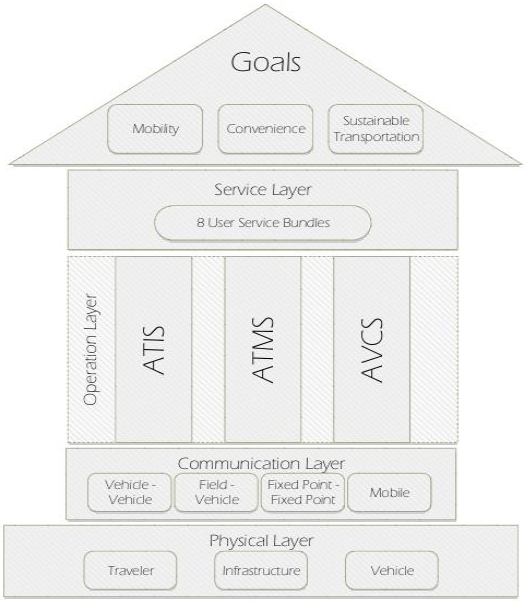


Figure 1.1 Architecture of ITS (Lin et al., 2017)

1.2.2 Transit Operation and Quality of Service

Regular examination and improvement of public transport service performance are critical for transit agencies given limited funds and expanding public needs. Performance review can assist transportation agencies identify failing services, prepare for new investments, justify existing investments, overcome difficulties and achieve success. (Wei et al., 2017). Nowadays the success of a public transport system depends on the number of passengers which the system can attract and keep. For this reason, the quality of a service becomes an issue of highest significance since it is known that an improvement in the degree of quality of the service leads to higher satisfaction of the passengers and an increase in the usage of the system(De Oña et al., 2013).

Service quality is connected to a range of factors characterizing the Public Transport (PT) service. (Berry et al., 1990) Many authors have also supported that "customers are the sole judges of service quality." Therefore, if service quality is judged from the customer's perspective, transit quality depends on the passengers' views about each feature characterizing the service.

(Kittelson & et al., 2003) Present a handbook on Transit Capacity and Quality of Service (TCQSM). The manual intends to establish criteria to determine the quality of service given to public transit passengers and calculate the capacity for various forms of transit. The TCQSM defines the Quality of Service (QOS) as the complete

measured or perceived performance of public transportation from the customer's perspective.

Levels of Service LOS, on the other hand, are a set of values for a given service measure, such as "A" (highest) to "F" (lowest), based on a transit customer's assessment of a certain component of transit service (Alkiswani, 2022).

The LOS defined in terms of the passengers' convenience in the urban transport service, dependent on the service headway, as illustrated in Table 1.1. The transportation services that have LOS lower than "C" are judged uncomfortable for the passengers. Also, the degree of service for a Fixed Route Service based on a travel time differential between private cars and public vehicles displayed in Table 1. 2 (Alhatemi & Alçura, 2022; Transportation Research Board, 2000).

Table 1.1 LOS based on Vehicle Delay

LOS	Description	Average Control Delay per Vehicle
A	Free flow	≤ 10 seconds
B	Stable flow (slight delay)	>10 – 20 seconds
C	Stable flow (moderate delay)	>20 – 35 seconds
D	Approaching unstable flow	>35 – 55 seconds
E	Unstable flow (high delay)	>55 – 80 seconds
F	Breakdown, forced flow	>80 seconds

Table 1. 2 LOS Based on Travel Time Difference

LOS	Description	Travel Time Difference (min)
A	Free flow	<0
B	Stable flow (slight delay)	1-15
C	Stable flow (moderate delay)	16-30
D	Approaching unstable flow	31-45
E	Unstable flow (high delay)	46-60
F	Breakdown, forced flow	>60

1.2.3 Transit Signal Priority

There is a considerable gap in research regarding the development of a clear methodology for evaluating the effectiveness of transportation systems. First, both running transportation systems effectively and providing equal access are necessary for its success. However, these two principles sometimes conflict. For example, focusing on servicing regions with fewer mobility alternatives may lead to greater cost and lower usage, while promoting efficiency might leave some groups neglected. This generates a requirement to achieve a careful balance between efficiency and equality in service provision. To examine this equilibrium, specialist models are needed. Therefore, it's necessary to create approaches that evaluate both efficiency and equal access while giving a complete analysis of transit service performance (Wei et al., 2017).

To increase the use of public transport, a primary way to reduce congestion in urban transport networks, it is necessary for public transit to run reliably. One effective method is to reduce transit delay at signalized junctions. Transit signal priority (TSP) emerged as a solution to increasing urban congestion and the desire for more reliable public transportation. TSP is a technological strategy that enables public transit vehicles (typically buses or trams) to receive preferential treatment at traffic lights. This is generally accomplished through various methods, such as extending green time, truncating red time, or reordering signal phases as a public transit vehicle approaches (United States Department of Transportation, n.d.). This is done without disrupting the overall coordinated signal plan for other vehicles. The goal is to reduce delays, improve schedule adherence, and enhance public transit reliability. This technology first appeared in the 1970s in cities such as Zurich, Stockholm, and Munich, using loop detectors and basic actuated controllers to detect transit vehicles and adjust signal timing accordingly. In North America, Seattle's King County Metro began TSP pilot programs in the 1980s using Automatic Vehicle Identification (AVI) systems (later replaced by GPS) (Skabardonis, 2000). This early wave of TSP laid the groundwork for what has become a globally adopted tool in transit operations. By the 2000s, TSP systems had developed from fixed-point detection to Automatic Vehicle Location (AVL) systems based on GPS and real-time communication systems. (Liao & Davis, 2007) demonstrated through simulation that AVL systems, GPS, and wireless

communication enable buses to accomplish priority requests more reliably, reducing delays and improving punctuality. Recently, some researchers have applied deep reinforcement learning (DRL) to TSP control systems. (Long et al., 2022) presented an extended approach to deep reinforcement learning in a connected vehicle environment, demonstrating improved transmission efficiency in simulations.

TSP has been widely applied in urban bus systems across multiple cities, delivering significant improvements in efficiency, safety, and service reliability. In Portland, Oregon, TriMet implemented GPS-based Transit Signal Priority (TSP) along 17 bus corridors, utilizing strategies such as green extension and early green activation. A safety evaluation using an interrupted time series model revealed a 4.5% reduction in overall crashes, including a 10% decrease in property-damage-only incidents. However, it noted slight increases in pedestrian and cyclist crash rates (Song & Noyce, 2019). Also, in Minnesota, the application of TSP on Metro Transit's Route 5—a high-ridership bus line—was shown to significantly reduce speed volatility, a surrogate safety measure, when TSP was active. This suggests that, beyond improving schedule adherence, TSP also promotes safer bus operations by smoothing traffic flow (Song et al., 2021). Finally, Several studies on TSP have been performed, either by evaluating empirical data or by using simulation methods. (Currie et al., 2007, 2013; He et al., 2011; Lee et al., 2005). Most of these studies focus on bus signal priority, while relatively few address trams.

Since the 1990s, many academics have focused on the modern tram, which is considered an efficient and eco-friendly public transportation option; nonetheless, its effectiveness relies on sufficient space and signal priority to guarantee maximum efficiency and service quality. Early studies, such as the TSP system for the Nottingham Express Transit, demonstrated by (Gatenby & Fedzin, 2004), reduce tram delays through the use of early green activation. Conversely, this led to increased delays for cars at busy intersections. Similarly, (Skabardonis & Christofa, 2011), found that TSP reduced transit delays while increasing non-priority vehicle delays at high-traffic junctions, with the impact varying from modest to considerable depending on intersection saturation. Considering these trade-offs, (Jeong & Kim, 2014) proposed the TRAMBAND model, which is a passive TSP

strategy and is an extension of the MAXBAND model for trams on exclusive median rails. This method optimizes tram bandwidth and minimizes general vehicle delay by utilizing dwell-time variability as waiting time, so that tram intersection delays can be reduced by as much as 6% and stops by 32% in a VISSIM simulation at nine intersections. From a different perspective, (Zhou et al., 2019) introduced the linking of conditional TSP strategies, early green, green extension, and phase insertion, with tram schedule optimization conducted to reduce total person delay. Looking at trams in semi-protected rights of way, the model of their algorithm re-times arrival and departure times to minimize the number of stops without unduly punishing cross traffic and achieves a weighted person delay of 56 seconds on the Ningbo tramline, versus 95 seconds when considering only tram delays (Zhou et al., 2019) also, in Toronto, Canada, the King Street Pilot program combined the TSP with early green extensions and green spaces across 18 intersections. A city report found that after the TSP was implemented in July 2018, tram travel times along the corridor were reduced by 30–126 seconds, depending on the direction, with an average saving of 8 seconds per intersection stop (City of Toronto, 2019). Similarly, a 2024 study in Marymoncka and Grochowska Streets in Warsaw utilized adaptive signal control with active priority for trams, demonstrating up to 25% savings in travel time and a 23% reduction in energy consumption through simulation modeling (Czerepicki et al., 2021). In Istanbul, a city with severe congestion and a growing tram network, TSP could enhance transit reliability. The T1 tram line, which serves high-density areas such as Eminönü and Bağcılar, frequently experiences delays due to mixed traffic and pedestrian congestion (IBB, 2022). Implementing TSP strategies could reduce travel times, aligning with Istanbul's mobility goals.

Globally, all of these contemporary efforts reflect a clear trend of combining signal timing strategies (green extension/red contraction) with adaptive controls focused on energy and equity, leading to measurable benefits such as reduced travel time, lower energy consumption, and improved access to economic opportunities.

1.2.3.1 Types of TSP:

Current TSP techniques can be categorized into three main types: passive priority strategies, active priority strategies, and real-time priority strategies. (Ma & Yang, 2010; Smith et al., 2005).

Passive priority strategies do not specifically identify the actual existence of a transit; they do not require the presence of the transit vehicle to be active, and therefore cannot dynamically reflect the impact of a strategy on traffic operation at a junction.

Active priority strategies give preference to public transit vehicles that are detected by sensors. These strategies include actions like:

- Green Phase Extension: Extends the current green signal, allowing a public transit vehicle to cross the intersection without stopping.
- Early Green Activation (or red truncation): Reduces the red signal time and initiates the green phase earlier than the specified time when a public transit vehicle is detected.
- Special Transit-Only Phase: Include a designated phase where only public transit vehicles are permitted to proceed, typically avoiding conflict with other traffic.
- Suppression of Conflicting Phases: Cancels or delays the green signal time for vehicle or pedestrian phases that interfere with the movement of a public transit vehicle.

In active priority mode, the system detects an approaching transit vehicle (e.g., a tram or bus) and temporarily modifies the regular signal timing to give that vehicle priority. This adjustment happens dynamically and overrides the current signal plan to reduce delays for the detected transit vehicle.

Real-time priority strategy is to optimize protocols according to one specific indication and to deliver priority signals for buses based on recognized real-time data (Liu et al., 2020; Ma & Yang, 2010).

According to (Marangon, 2018; Wahlstedt, 2014) some of the most frequent transit priority systems that could be given as examples are:

- SCOOT

It is a self-optimizing signal system built for linked traffic networks. It uses a centralized structure to interact directly with all signal controllers in the network, trying to improve the entire area. The system changes offset every cycle, updates the cycle time every five minutes, and adjusts the green signal split just a few

seconds before each stage change. To keep stability, SCOOT makes only slight changes from one cycle to the next. However, it does not predict bus times at stops, so bus monitors need to be placed downstream of the nearest bus stop. This system was developed in the UK and has been widely implemented in cities such as London and Southampton. Field trials in these cities have shown significant benefits for buses (Bretherton et al., 1996).

- PRIBUSS

The PRIBUSS (Prioritizing Buses in Coordinated Signal Systems) is a set of technologies designed to offer bus priority at traffic signals with active transit priority systems. It involves six basic processes for bus priority:

- Extension of the ongoing green.
- Re-taken start
- Early green
- Extra stage
- Double early green
- Double extra stage

PRIBUSS programming in the signal controller employs operations to trigger one of these six procedures. However, there is no systematic way inside PRIBUSS to prioritize amongst transits when several conflicting priority requests occur. In such cases, the system employs a "first-come, first-served" philosophy to settle disagreements. PRIBUSS has been tested and implemented in Swedish cities, including Stockholm, to reduce bus travel times and improve public transport efficiency(Davol, 2001).

- SCATS

The Sydney Coordinated Adaptive Traffic System (SCATS) combines a plan selection system with a self-optimizing system. It functions at two levels: a tactical level that manages the cyclic variations in demand at specific junctions and a strategic level that uses regional computers to calculate the best cycle length, phase splits, and offsets to fit the current traffic circumstances. Although unique stages can also be started, SCATS mostly employs red truncations and green extensions to provide priority to buses and trams. SCATS manages competing priority requests in a "first-come, first-served" pattern. On major

roadways, SCATS works very well for producing green waves. The SCATS system originated in Sydney, Australia, and is widely used in all Australian cities, managing approximately 11,000 signal-controlled intersections. It has since spread globally, with SCATS being implemented in more than 180 cities in 28 countries (Transport for New South Wales (TfNSW), n.d.).

1.3 Research Objectives and Questions:

The main aim of this research is to analyze and evaluate the benefits of using the tram priority technique at the Turgut Özal Millet Cd intersection in Istanbul. The objectives of this research can be summarized as follows:

- Assess Current Intersection Performance: Analyze the present traffic conditions at the intersection with trams, pedestrians, and private cars.
- Develop priority situations: Create scenarios where trams are assigned priority at the junction.
- Evaluate Impacts: Measure the impacts of tram priority on traffic flow and efficiency for all users (trams, pedestrians, and private cars).
- Identify optimal plan: Determine the most effective tram priority plan that balances the demands of trams, pedestrians, and private autos.
- Provide Recommendations: Offer realistic advice for implementing tram priority strategies in urban crossings.

To evaluate the current situation, the effectiveness of the suggested strategy, and the achievement of the desired objectives of the research, the research questions are summarized as follows:

- Present Performance: What are the present traffic flow patterns and congestion levels at the intersection, and how do trams, pedestrians, and private automobiles now interact at this intersection?
- Priority circumstances: What are the various circumstances for prioritizing trams at the intersection, and how can each possibility be realistically realized within the existing infrastructure?
- Impact Evaluation: How do alternative tram priority scenarios affect the travel times and delays for trams, pedestrians, and private cars, and how do

these scenarios affect overall transportation efficiency and congestion levels?

- Optimal Strategy: In which period does the tram TSP offer the optimum balance between boosting tram efficiency and minimizing conflict with pedestrians and private cars?
- Recommendations: What are the possible difficulties and solutions for implementing the proposed tram priority strategy?

2
METHODOLOGY AND SITE DESCRIPTION

2.1 Overview

The primary goal of this research is to examine the impact of installing a tram priority system on users and to evaluate the benefits of integrating a tram priority system into public transport. To this goal, a traffic signal junction with a tram running through was used as a case study. Two scenarios were set up and modeled, one with a tram priority system and the other without it. These two scenarios have been analyzed to compare their performance and consequences.

This chapter explains the research methods employed in the study. It begins with a full explanation of the present condition in the selected area, including observations from the site visit. This is followed by an explanation of the procedures utilized for traffic statistics and data gathering.

At the intersection under study, the following data were collected to support the analysis:

- Vehicle composition
- Pedestrian activity
- Traffic light program
- Lane width and number of lanes
- Bus frequency
- Tram length and arrival times (data received from IETT and compared with field data).
- Traffic volumes (Data was obtained in the field.)

These statistics provide a foundation for analyzing the scenarios and estimating the impact of the tram priority system on the intersection's functioning and user experience.

Suitable traffic simulation software was used to model the base and proposed scenarios. Over the years, several traffic simulation programs have been developed, each having distinct characteristics. For this work, the focus was on finding software with features that facilitate studying the effects of ITS. After thorough research, VISSIM software was identified as the most suitable alternative for this purpose because it offers numerous features, including traffic signal control algorithms, and provides a free version for research and academic purposes, as well as the program's ease of use.

2.2 Site Selection and Description

Study Location: “Turgut Özal Millet Caddesi” Intersection shown in Figure 2. 1. “Turgut Özal Millet Cd” Intersection was chosen as the research location because of its significant traffic activity and its importance as a tourist attraction. Key features of the intersection include many factors, such as it experiences considerable congestion, with approximately 700 vehicles per hour in both directions during peak hours. In addition to the heavy presence of public transportation, such as the T1 tram line, which runs through the intersection, and 38 bus lines servicing a range of routes. Without forgetting the existence of a pedestrian crossing with considerable traffic throughout the day (Approximately 700 pedestrians per hour during peak hours and 1,000 pedestrians per hour during off-peak hours).



Figure 2. 1 Turgut Özal Millet Cd Intersection (Google Earth, n.d.)

All of this shows the intersection as an essential junction for cars, pedestrians, and public transportation, highlighting its value for this research.

Bus lines passing through the intersection: The intersection is served by a total of 38 bus lines, including: 145M, 145T, 28T, 31, 32A, 33, 336Y, 33B, 33E, 33Y, 35D, 36, 36ES, 46T, 71T, 72T, 73, 73F, 76D, 79E, 82, 85T, 89, 89B, 89C, 89K, 92, 92B, 92C, 92K, 92T, 93, 93T, 94A, 97, 97A, 97BT, 97T.

The tram line under examination is the T1 Kabataş-Bağcılar tram line, as shown in the Map 2. 1. The first section of the line was completed between Sirkeci and Aksaray, and the line was commissioned in 1992. The line is linked to Topkapı and Zeytinburnu directions, and thereafter the line is expanded up to Eminönü Station. Later on, on 30th January 2005, the line traveled over Galata Bridge and linked to Findikli.

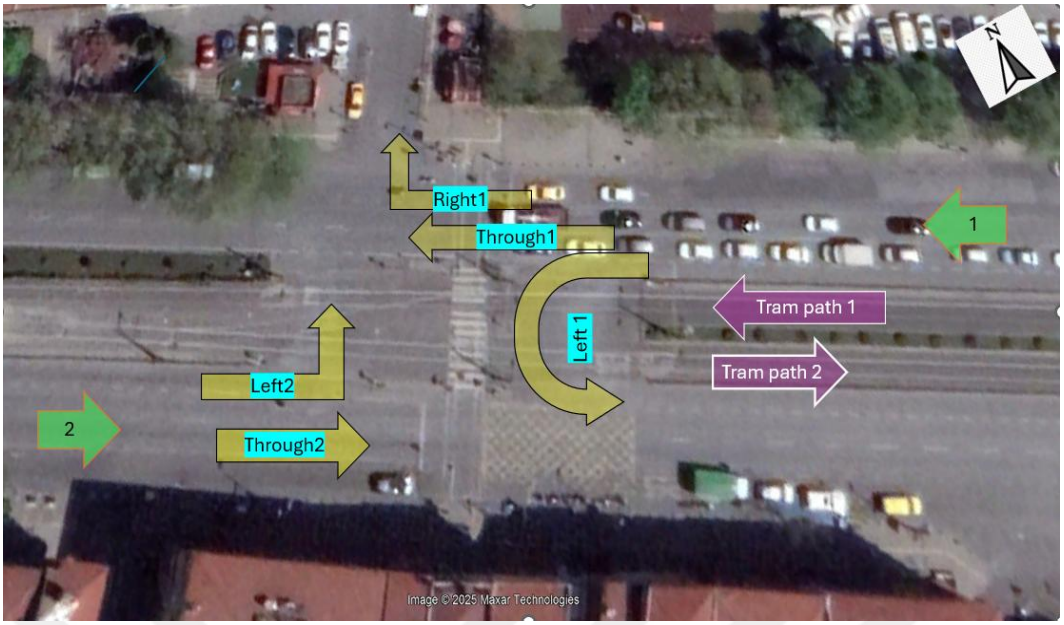
All stations of the T2 Zeytinburnu - Bagcilar Line, which was commissioned in 2006 and is operated by high-floor tram cars. The route was made compatible with low-floor trams within a single weekend and then linked with the T1 route on February 3, 2011. Direct train service from Bagcilar to Kabatas was provided with this technique(Kabatas-Bagcilar Tram Line, n.d.).



Map 2. 1 T1 tram line (*Istanbul regional line T1*, n.d.)

The T1 tram line spans a total length of 19.3 kilometers and consists of 31 stops. It operates with 92 vehicles, providing a travel time of approximately 65 minutes. The tram operates daily from 6:00 AM to 12:00 AM, serving an impressive 370,000 people every day. With 295 one-way trips done daily, the line maintains a high journey frequency of barely 2 minutes during peak hours, assuring efficient and dependable service (*Kabatas-Bagcilar Tram Line*, n.d.).

Turgut Özal Millet Cd Road stretches in two directions, as shown in Map 2. 2 ,each was identified with a distinct number for reference in this study. The first path, referred to as Path 1, extends from southeast to northwest, starting from Atatürk Blv. Street and terminating at Topkapı Kavşağı. This road contains a straight part, a right turn, and a left turn. Before the intersection, it consists of four lanes, which merge into two lanes after the intersection. The second path, referred to as Path 2, extends from northwest to southeast, commencing at Topkapı Kavşağı and terminating at Atatürk Blv. Street. This road contains three lanes that remain the same number after the intersection and includes a parking lane allocated for cars turning left. These two approaches constitute the basis of the analysis done in this paper.



Map 2. 2 Movement directions at the intersection

2.3 Traffic Count and Data Collection

Data was collected from relevant authorities to analyze and evaluate the initial and proposed scenarios, and through field surveys to provide any missing data. Traffic signalization programs were taken from IBB and validated on-site, while tram departure timetables were sourced from Metro Istanbul and reviewed for accuracy. Manual traffic data was collected for the specified routes, classifying vehicles into private automobiles, public transit buses, bicycles, and trucks (combining heavy and light trucks into one category). Additionally, the number of pedestrians crossing in both directions was recorded. Data were gathered at 10-minute intervals for one hour during three separate periods—8:00 to 9:00 a.m., 12:00 to 1:00 p.m., and 5:00 to 6:00 p.m.—on November 26,27, and 28 to capture traffic patterns during and outside peak hours.

The tram departure times from the main stations were taken from IETT and processed by adding the average time it takes to reach the intersection under study. These times were taken from Google Maps, to determine the tram arrival times at the intersection

2.4 Measurements Used for Evaluation

To compare the real situation with the supposed scenarios, a thorough set of metrics was applied. This included queue length, both average and maximum, as well as the general level of service at the intersection. Traffic performance parameters such as average vehicle delay, average passenger delay, and average stopped delay were also studied to determine efficiency. Environmental consequences were investigated by emissions assessments, including carbon monoxide (CO), nitrogen oxides (NOx), and volatile organic compounds (VOCs). Additionally, fuel consumption statistics were incorporated to offer insights into energy efficiency. Together, these parameters gave a clear basis for comparing and evaluating the efficacy of the proposed scenarios against the base model. PTV VISSIM estimates vehicle emissions by using external emission models, as the internal emission module doesn't have detailed calculations. Second-by-second vehicle trajectory data, such as speed, acceleration, and operational status, are obtained from the simulation program. These trajectories are input into a model such as Bosch's cloud-based Air Quality platform that uses vehicle and powertrain specifics to calculate emissions of pollutants (e.g., CO, NOx, and VOC) and fuel consumption according to simulated driving behavior and vehicle types (*Traffic Simulation Software | PTV Vissim | PTV Group*, n.d.).

Table 2. 1 Evaluation measurement description (PTV Group, 2025)

Measurement type	Description
Queue length	Average queue length[m]: The current queue length is measured in each time step, and the arithmetic meaning is thus calculated per time interval.
Maximum queue length	Queue length (maximum)[m]: In each time step, the current queue length is measured, and the maximum is thus calculated per time interval.
Level of service	Level-of-service (A... F) as computed by the associated LOS scheme (Table 1.1)
Average vehicle delay	The delay of a vehicle in (s) in leaving a travel time measurement is obtained by subtracting the theoretical (ideal) travel time from the actual travel time.
Average Person delay	Delay of all passengers in seconds without passenger service times at stops
Average stopped delay	Stopped delay per vehicle in seconds without stopping at PT stops and in parking lots
CO Emissions	Quantity of carbon monoxide [grams]
Nox Emissions	Quantity of nitrogen oxides [grams]
Volatile organic compounds Emissions	Quantity of volatile organic compounds [grams]
Fuel consumption	Fuel consumption [US liquid gallon]

3
MODELING AND SIMULATION RESULTS

3.1 Overview

This chapter contains a full evaluation of the traffic assessments and simulation data for both the baseline and suggested scenarios. The simulation process was divided into two phases: the first phase represented the baseline scenario without the deployment of intelligent systems, and the second phase focused on the proposed scenario with the implementation of intelligent systems.

To assure accuracy and reliability, each simulation was run over a total time of 80 minutes, which comprised a 15-minute warm-up session, a 60-minute study period, and a 5-minute cool-down period(*KA-04927 · Customer Self-Service*, n.d.; PTV Group, 2025). A warm-up period is used in simulations to stabilize traffic conditions before data collection begins. During this initial phase, vehicles are generated and distributed across the network, allowing traffic flows, queues, and delays to reach a realistic steady state. While the cool-down period is used after the main evaluation phase to allow vehicles to exit the network naturally, preventing sudden termination effects.

The evaluation employed the effectiveness indicators supplied by the VISSIM software, as stated in the preceding chapter, to evaluate the performance of public transit and junctions. It is worth noting that the simulation process was repeated 10 times for each scenario(Dowling et al., 2004).

A significant component of the suggested main strategy is implementing a tram priority system utilizing a green extension technique. This strategy improves the duration of the green signal for incoming trams, decreases delays, and improves the overall efficiency of public transit. The chapter evaluates the advantages to

transport routes and intersections achieved by this technique, focusing on its potential to improve urban mobility.

3.2 Network Design Characteristics and Settings Selections

The network for the selected intersection was created with the academic version of VISSIM, PTV VISSIM 2025, following the rules and guidelines given in (PTV Group, 2025). When building connections in VISSIM display road lanes, the behavior of all links was identified as Urban (motorized) to manage speed situations at intersections and stops. This behavior contains a range of parameters that were established, including:

- The kind of vehicle model that follows was set to Wiedemann 74.
- The lane change rule was set to Free Lane selection.
- Both Left Overtaking and Right Overtaking were enabled and set to (Default) to allow cars to overtake

The Wiedemann 74 car-following model, invented by Rainer Wiedemann in 1974, is a major instrument used in traffic simulation software like PTV VISSIM. It mimics how drivers behave by separating their actions into multiple states, dependent on how close they are to the automobile in front and how quickly that car is driving(PTV Group, 2025; Wiedemann, 1991). This model is highly useful in contexts such as city roadways, signalized crossings, and urban traffic networks(Higgs et al., 2011).

The maximum speed for private cars, motorcycles, trucks, and public buses has been set at 50 km/h, and 40 km/h for trams, in accordance with the allowable speed limitations stated in (*Hız Sınırları*, n.d.; *Kabatas-Bagcilar Tram Line*, n.d.)The number of passengers on each tram was set at 200, which represents the maximum capacity of the tram, as the actual number exceeds its maximum capacity. Also, the passengers on the buses on the network were set between 40 and 60, as an estimated value due to the lack of data.

3.2.1 Base Model

The streets were given the same numbers mentioned in Chapter Two, and the traffic signals were numbered clockwise, starting from street number 1 until 6 (signal traffic ID). Creating a VISSIM network requires a number of processes aimed at

correctly simulating traffic flow at the intersection under study. The process began with collecting necessary data, including road layouts, traffic numbers, signal timings, and other relevant information. This data served as the basis for developing a virtual network model.

The initial stage involved importing a background map of the intersection from Bing Maps into VISSIM, which provided a reference for creating the road network. Road connections were then created using VISSIM tools, providing properties such as the number of lanes, lane lengths, and other geometric aspects. Connectors were created to connect road segments at intersections and turning locations, ensuring realistic traffic flow as shown in Figure 3. 1 and Figure 3. 2.

Intersections were controlled by assigning traffic signal systems, defining signal sets, and creating timing plans. A pedestrian path was also created to depict the pedestrian movement. Vehicle demand was modeled by establishing vehicle entry locations at major road entrances, with traffic volumes and routing decisions determined to distribute vehicles around the network efficiently.

To model public transport, transit routes and timetables were integrated to simulate bus and tram movements. The network was further improved by adding low-speed zones and changing driver behavior factors, which helped replicate more realistic traffic conditions.

The final network underwent simulation testing to detect and fix any issues, such as disconnected links or unrealistic vehicle behavior. Once approved, the network was used to collect performance metrics, including delays, travel times, queue lengths, and emissions, which were then examined to evaluate the system's performance.

These procedures ensured that the VISSIM network was accurately generated and operated efficiently, simulating actual traffic situations and making it easier to evaluate various traffic scenarios.

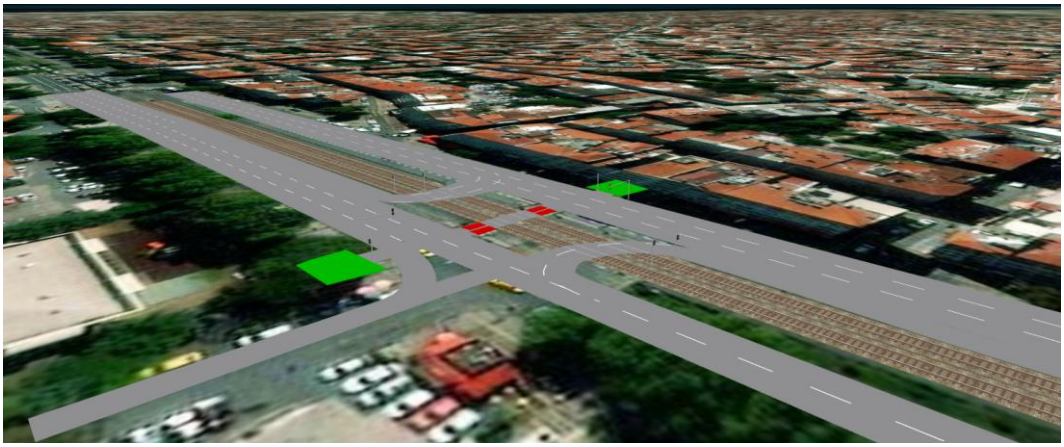


Figure 3. 1 3D Visualization of the Simulated Network in VISSIM

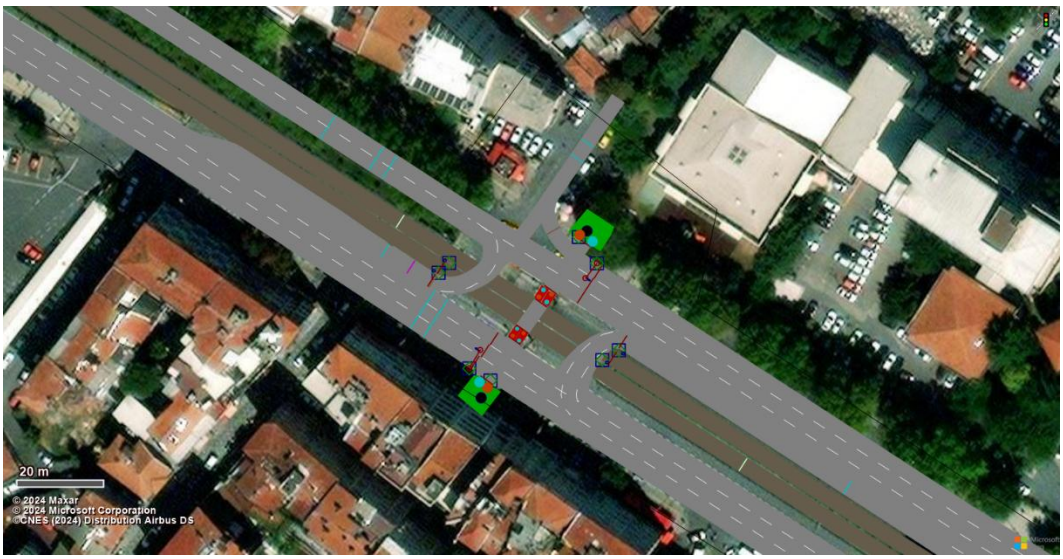


Figure 3. 2 2D Visualization of the Simulated Network in VISSIM

3.2.2 Proposed Scenario

A green extension strategy was implemented, prioritizing tram crossings in the proposed scenario. Detectors were installed in both directions to monitor tram arrivals and were integrated with the VISVAP system in VISSIM. A control scheme was developed for the signals, with a maximum green extension duration of 20 seconds. This period was chosen as the time it takes for a tram to cross a traffic light from the moment it enters the network, allowing any tram within the network during the green signal time to cross. Four detectors were placed in each direction, 55 meters apart, to facilitate the strategy. This distance was chosen because it is less than the length of the tram, ensuring that the detectors can monitor the tram throughout its time on the network (Figure 3.4). As shown in Figure 3.3, the strategy begins by checking which phase is active. If the active phase is stage 1(tram green

extension phase), it checks for the presence of the tram on the network. If a tram is detected by sensors, it extends the green time until it is safe to cross the intersection. If no tram is detected, it will wait until the time of this phase is completed and it will move to the next phase (stage 2). If the active phase is not associated with a tram (stage 2) , the strategy remains inactive and wait until this phase is completed and move to stage one again.

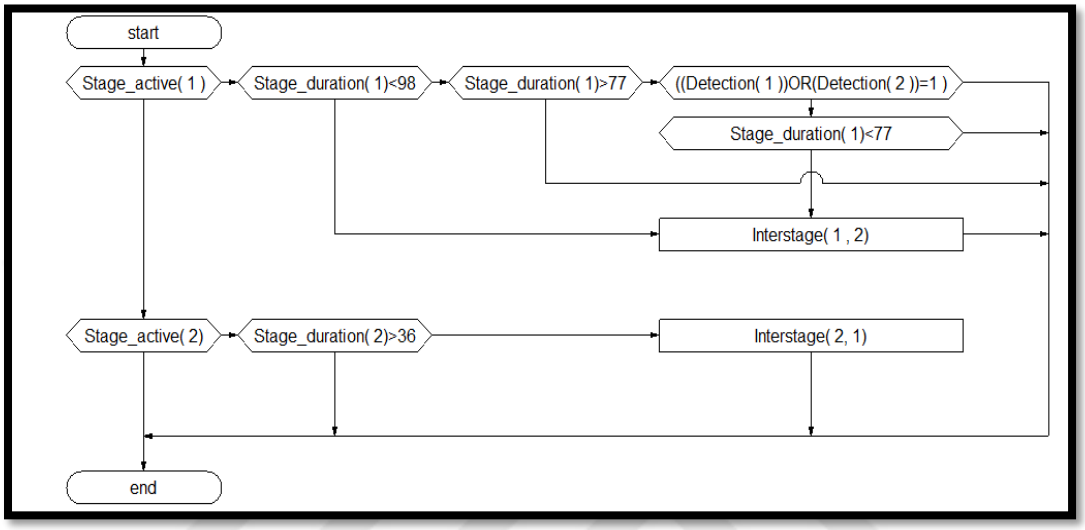


Figure 3.3 VISVAP flowchart

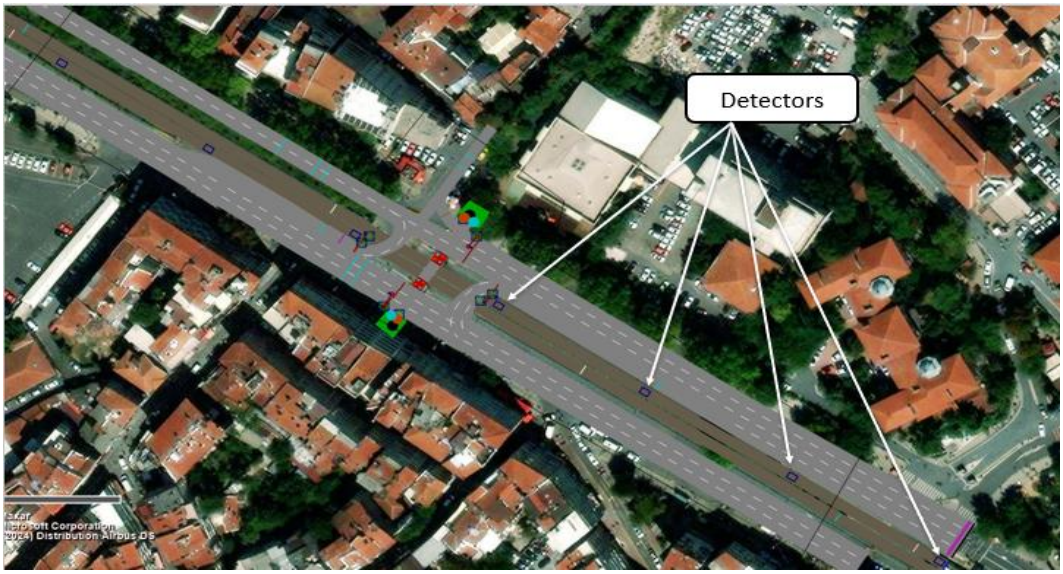


Figure 3.4 2D Visualization of the Proposed Network in VISSIM

3.3 Results

The simulations were conducted for the base model and proposed scenarios during the previously mentioned periods, and the results were as follows:

3.3.1 Base Model Results:

The performance of Turgut Özal-Melit CD intersection under original conditions without TSP strategies was evaluated during the morning peak period between 8:00 and 9:00 a.m. using VISSIM simulations. On the tram lines, the level of service (LOS) ranged between C and B for both routes, with queue lengths of 7 meters and 5.6 meters, and vehicle delays of 20.7 seconds and 16.5 seconds, respectively. Average fuel consumption was 75.95 gallons, with best-case scenarios 73.88 gallons and worst-case scenarios 78.69 gallons. Average delays per person at the intersection were 19.95 seconds, and the average person delay was 23.3 seconds. Full details are provided in the figures and tables below:

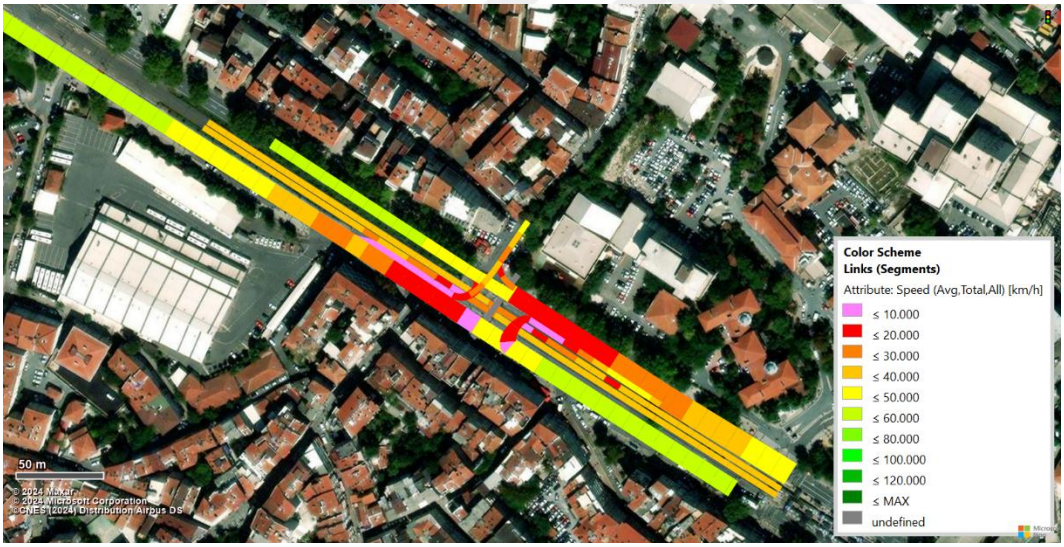


Figure 3.5 Speed of base model first case

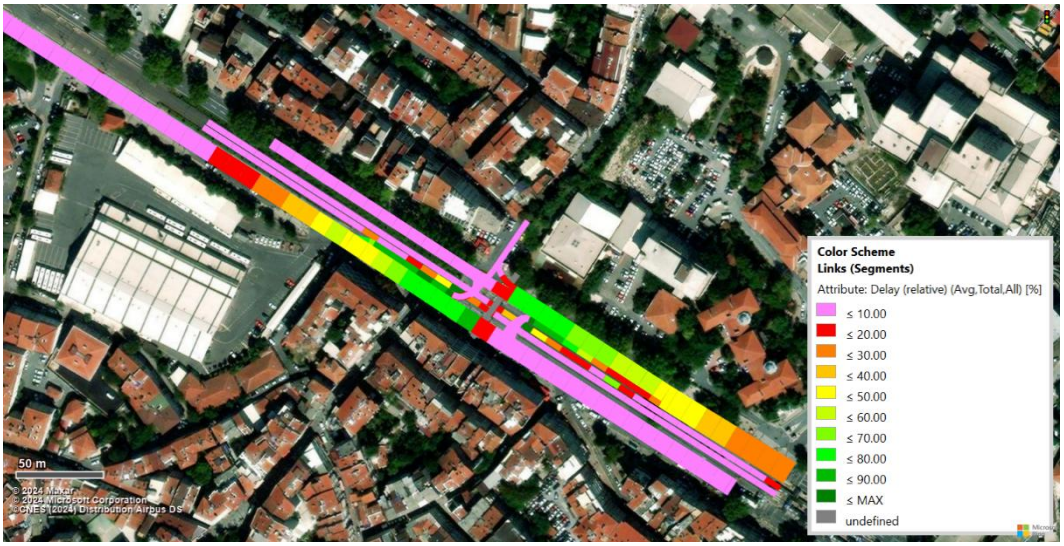


Figure 3.6 Relative delay of base model first case

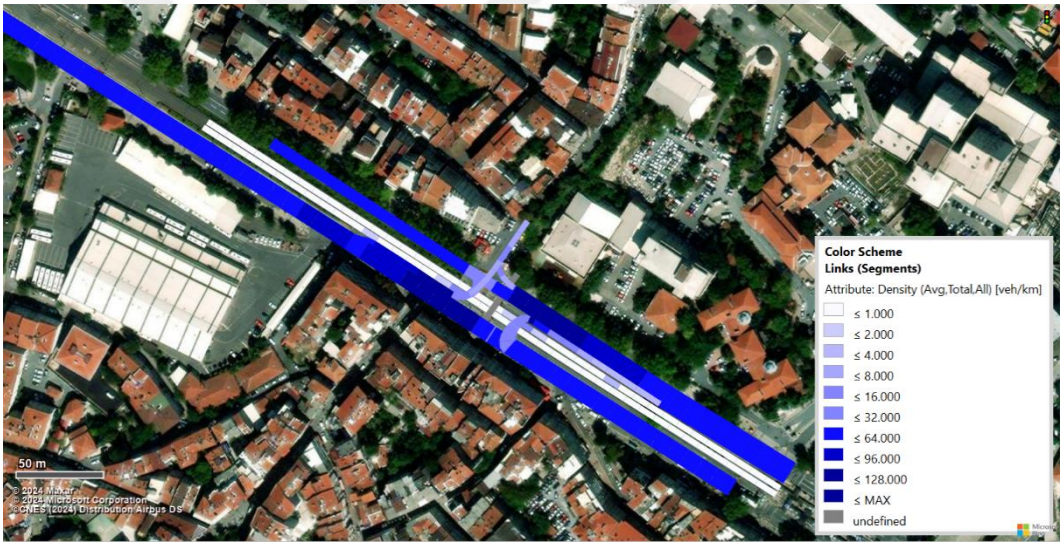


Figure 3.7 Density of base model first case

Table 3. 1 Base model first case general results

Movement	Queue Length (m)	No. of Persons	No. of vehicle	LOS	Vehicle delay (s/veh)	Person Delay (s/person)
Tram Path 2	5.60	5400	27	B	16.50	16.50
Tram Path 1	6.96	5400	27	C	20.73	20.73
Street 2 Straight	26.15	8169	1982	B	17.39	18.49
From 2 to 1 (U-turn)	42.39	196	196	E	65.21	65.21
From 2 to 1 Left Turn	42.39	183	183	E	66.50	66.50
From 1 to 2 (U-turn)	7.01	118	118	D	45.95	45.95
Street 1 Straight	35.95	7532	1660	B	19.89	20.84
Street 1 Right Turn	35.95	142	142	B	14.40	14.40
All Paths	20.68	27140	4335	C	23.30	19.95

Table 3. 2 Base model first case environmental results

Movement	**Emissions CO (gm)**	**Emissions Nox (gm)**	**Emissions of volatile organic compounds (gm)**	**Fuel consumption (gallons)**
Tram Path 2	28.18	5.48	6.53	0.40
Tram Path 1	29.97	5.83	6.95	0.43
Street 2 Straight	2334.32	454.17	541.00	33.40
From 2 to 1 (U-turn)	398.49	77.53	92.35	5.70
From 2 to 1 Left Turn	351.09	68.31	81.37	5.02
From 1 to 2 (U-turn)	187.50	36.48	43.46	2.68
Street 1 Straight	1872.65	364.35	434.00	26.79
Street 1 Right Turn	112.18	21.83	26.00	1.60
All Paths	5309.22	1032.98	1230.46	75.95

The remaining results for the second case (from 12:00 to 13:00) and the third case (from 17:00 to 18:00) appear in Appendix C and Appendix D.

3.3.2 Proposed Scenario Results:

The intersection performance was evaluated after applying TSP (green extension) strategies during the peak period between 8:00 and 9:00 a.m. using VISSIM simulations. For the tram paths, the level of service was A for both paths, with queue lengths of 2.46 and 2.08 meters and vehicle delays of 8.3 and 7 seconds. The overall average fuel consumption was 74.95 gallons. In the best-case scenario, it was 72.16 gallons; in the worst-case scenario, it was 77.7 gallons. The figures and tables below present detailed results. When we examined delay measurements, we found that the overall delay for persons was 15.78 seconds per person and 23.16 seconds for vehicles.

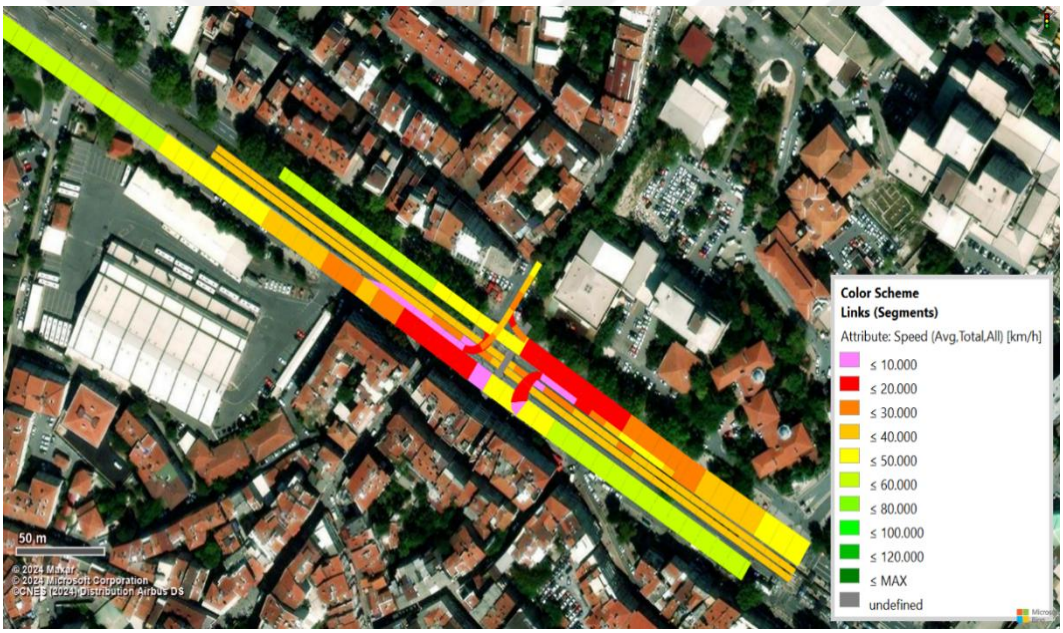


Figure 3. 8 Speed of the Proposed scenario first case

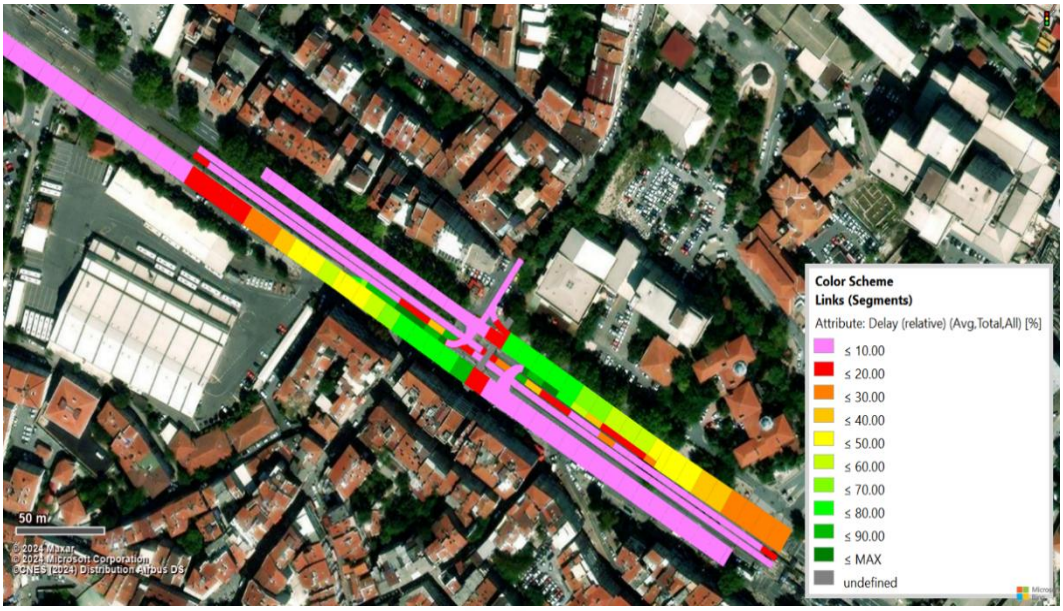


Figure 3. 9 Relative delay of Proposed scenario first case

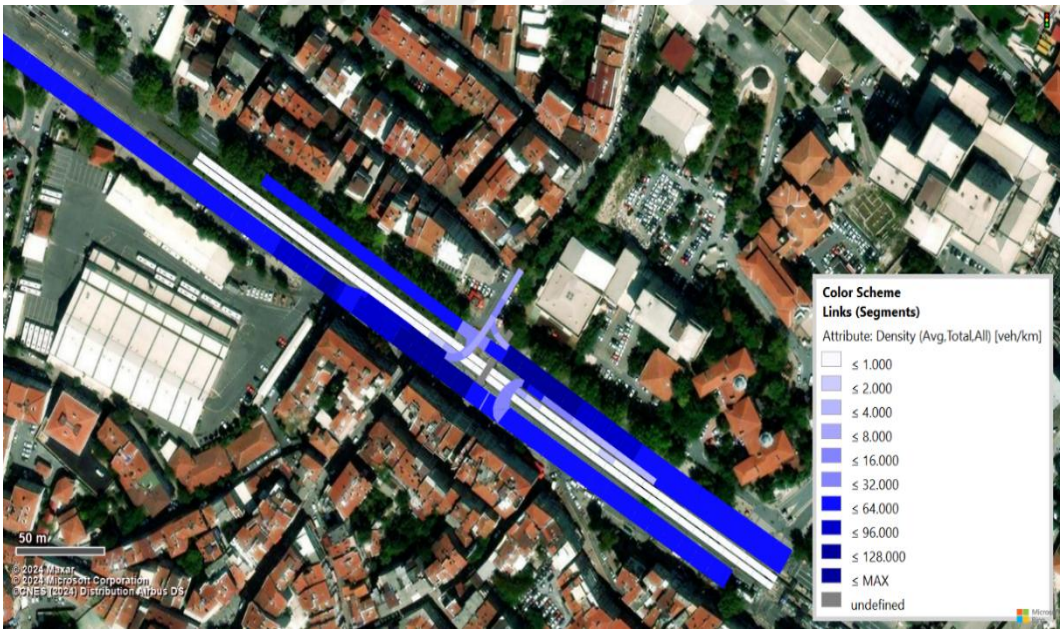


Figure 3. 10 Density of Proposed scenario first case

Table 3. 3 Proposed scenario first case general results

Movement	**Queue Length (m)**	**No. of vehicle**	**Persons**	**LOS**	**Vehicle delay (s/veh)**	**Person delay (s/person)**
Tram Path 2	2.08	27.00	5400	A	7.01	7.01
Tram Path 1	2.46	27.00	5400	A	8.36	8.36
Street 2 Straight	28.89	1971.00	1971	B	17.03	18.91
From 2 to 1 (U-turn)	45.68	195.00	195	E	70.75	70.75
From 2 to 1 Left Turn	45.68	182.00	182	E	68.74	68.74
From 1 to 2 (U-turn)	7.49	115.00	115	D	47.35	47.35
Street 1 Straight	34.96	1657.00	1657	B	19.42	20.82
Street 1 Right Turn	34.96	141.00	141	B	13.55	13.55
All Paths	20.26	4316.00	15062	C	23.16	15.78

Table 3. 4 Proposed scenario first case environmental results

Movement	**Emissions CO (gm)**	**Emissions Nox (gm)**	**Emissions of volatile organic compounds (gm)**	**Fuel consumption (gallons)**
Tram Path 2	23.61	4.59	5.47	0.34
Tram Path 1	23.79	4.63	5.51	0.34
Street 2 Straight	2292.29	446.00	531.26	32.79
From 2 to 1 (U-turn)	418.59	81.44	97.01	5.99
From 2 to 1 Left Turn	353.93	68.86	82.03	5.06
From 1 to 2 (U-turn)	185.48	36.09	42.99	2.65
Street 1 Straight	1841.35	358.26	426.75	26.34
Street 1 Right Turn	107.67	20.95	24.95	1.54
All Paths	5238.81	1019.28	1214.15	74.95

The remaining results for the second and third cases appear in Appendix E and Appendix F

4
CONCLUSION

In this chapter, we will conclude the thesis by obtaining the final data collection results and analyzing them to answer the study's research question and objectives outlined in Chapter 1. In this study, using PTV VISSIM and VISVAP, a comparison was made of a base model and a proposed scenario which included TSP, analyzing performance metrics like queue length, vehicle delay, person delay, CO emissions and fuel consumption over three time periods (8:00–9:00, 12:00–13:00, and 17:00–18:00) and an overall analysis evaluation. Using comparison tables and visualizations, we present the benefits and drawbacks of prioritizing tram movements at the intersection over outflow of other traffic flows.

This chapter creates these and related findings to illuminate their implications for urban transportation planning and policy. It explains the simulation results, emphasizing how TSP minimizes tram delays and impacts on vehicle traffic, environmental performance, and overall system efficiency. It discusses the trade-offs that have been seen, like longer waits at the intersections. It also explores study limitations (model assumptions, data constraints) and suggests opportunities for future research to refine TSP strategies. Finally, the thesis concludes by highlighting key lessons, making recommendations for policymakers and transportation planners, and emphasizing TSP's potential in contributing to sustainable urban mobility. This chapter attempts to contribute to a deeper discussion on improving public transport systems in congested urban environments.

4.1 Discussion

To assess the effectiveness of the tram priority strategy, traffic simulations were performed using both a base model (without tram priority) and a proposed scenario (with tram priority) during three time periods (8:00–9:00 a.m., 12:00–1:00 p.m.,

and 5:00–6:00 p.m.). It considers the main performance measurements, including queue length, vehicle delays, passenger delays, Level of Service (LOS), emissions (CO), and fuel consumption. The emphasis was on performance assessment, further on the tram lines, as well as on the overall performance of the network. The results indicate a considerable increase in tram performance with a diversity of other traffic flow effects. They also highlight potential trade-offs from tram priority in a mixed traffic environment.

- 8:00–9:00 AM (Morning Peak):

For the Tram Paths, the queue length for the proposed scenario achieved a 64.61% (from 6.96 m to 2.46 m) decrease of average queue lengths for Tram Path 1 and a 62.87% (from 5.60 m to 2.08 m) decrease for Tram Path 2. While in the case of the best scenario, reduced to (1.28 m and 0.52 m, respectively), suggested near-free-flow conditions. Also, for Vehicle and Person Delay, Tram Path 1 experienced a reduction of 59.70% for vehicle and person delay (from 20.73 s to 8.36 s). For Tram Path 2, vehicle and person delay (from 16.50 s to 7.01 s) decreased by 57.51%. The reductions are due to improved tram travel times, facilitated by priority signaling.

Level of Service (LOS) for Tram Path 1 was improved from C to A, and for Tram Path 2, it was improved from B to A, indicating that the service quality of the trams is excellent in the proposed scenario. Regarding environmental performance measures, emissions and fuel consumption, CO emissions decreased by 20.62% for Tram Path 1 (from 29.97 g to 23.79 g) and 16.21% for Tram Path 2(from 28.18 g to 23.61 g). Fuel consumption followed a similar trend, with 20.62% and 16.21% reductions, respectively.

Non-tram movements (e.g., Street 1, Street 2) showed mixed results for other Movements. Street 2 Straight experienced a 10.48% increase in queue length (from 26.15 m to 28.89 m), suggesting some congestion due to tram prioritization. However, vehicle delays remained comparable or slightly improved (e.g., -2.05% for Street 2) while the person delay at the same time increased by 2.25% (from 18.29 to 18.91 seconds per person).

U-turns and left turns (e.g., left turn 2) saw increased queue lengths (7.78%) and delays (5.91% for both vehicle and person delays), indicating that prioritizing trams occasionally delayed other vehicles at intersections.

Finally, the overall network showed a modest 2.01% reduction in queue length (from 20.68 m to 20.26 m) but a significant 20.91% reduction in person delay (from 19.95 s to 15.78 s), reflecting trams' high passenger capacity. CO emissions and fuel consumption decreased slightly (1.33%), but LOS remained at C (3), indicating no overall change in service quality for all vehicles. The overall results are shown below:

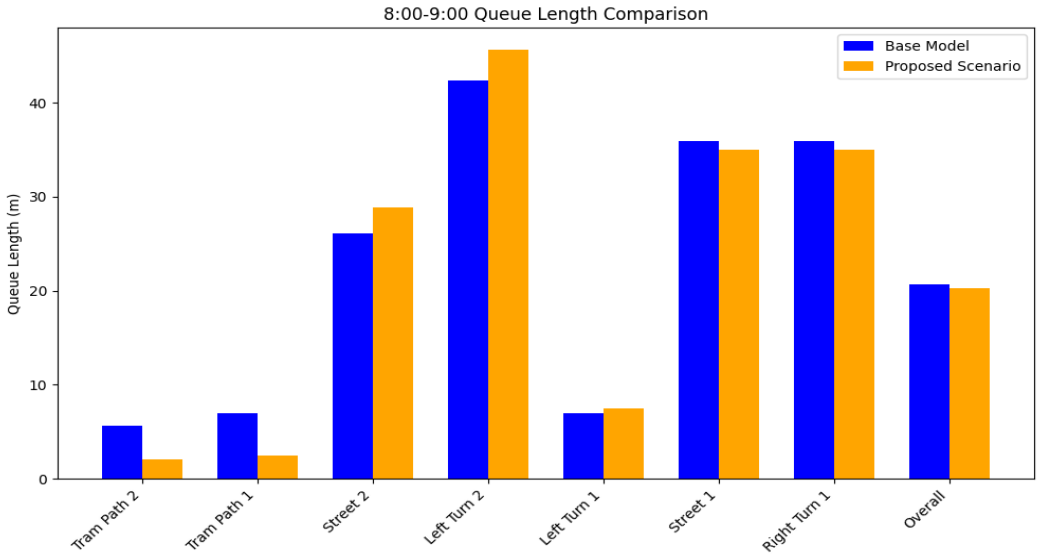


Figure 4.1 Queue length comparison (8:00-9:00)

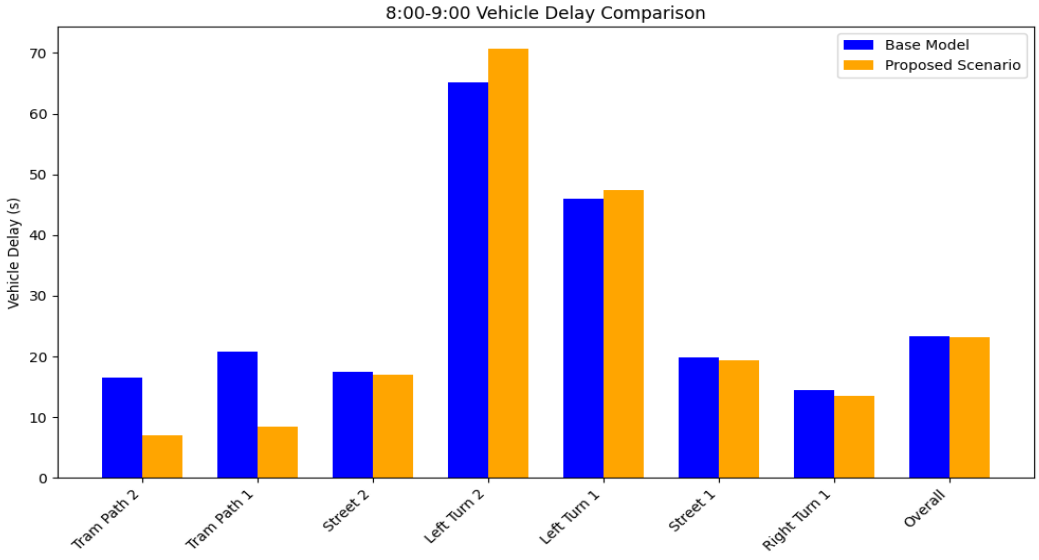


Figure 4. 2 vehicle delay comparison (8:00-9:00)

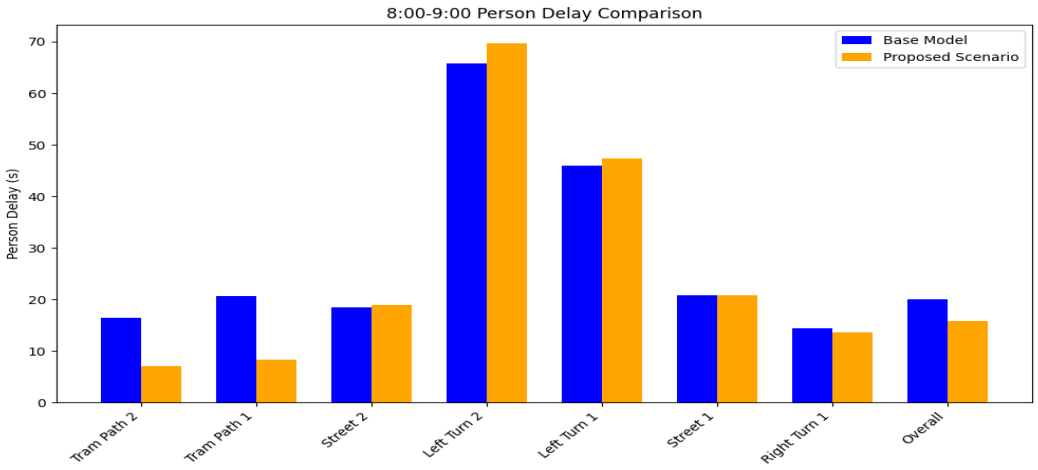


Figure 4. 3 person delay comparison (8:00-9:00)

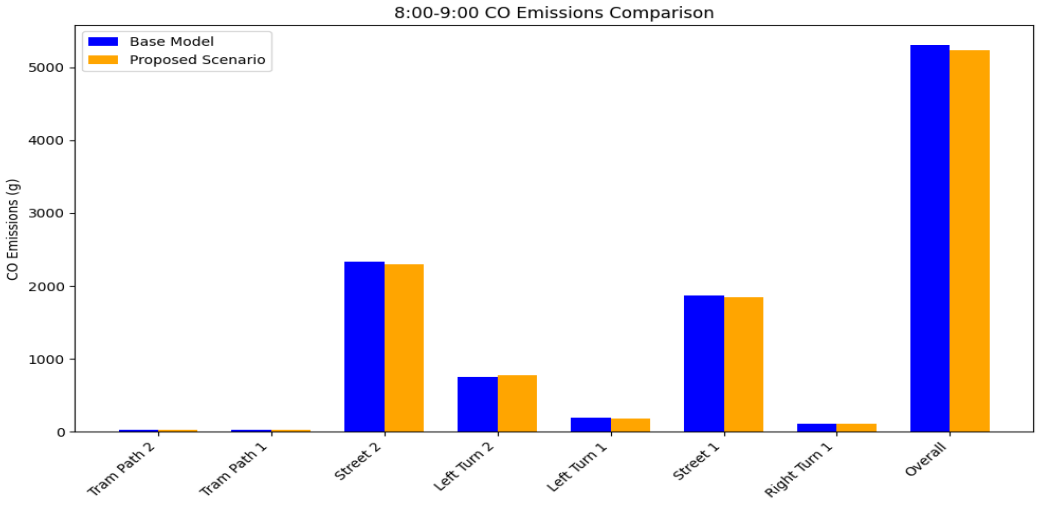


Figure 4. 4 CO Emission comparison (8:00-9:00)

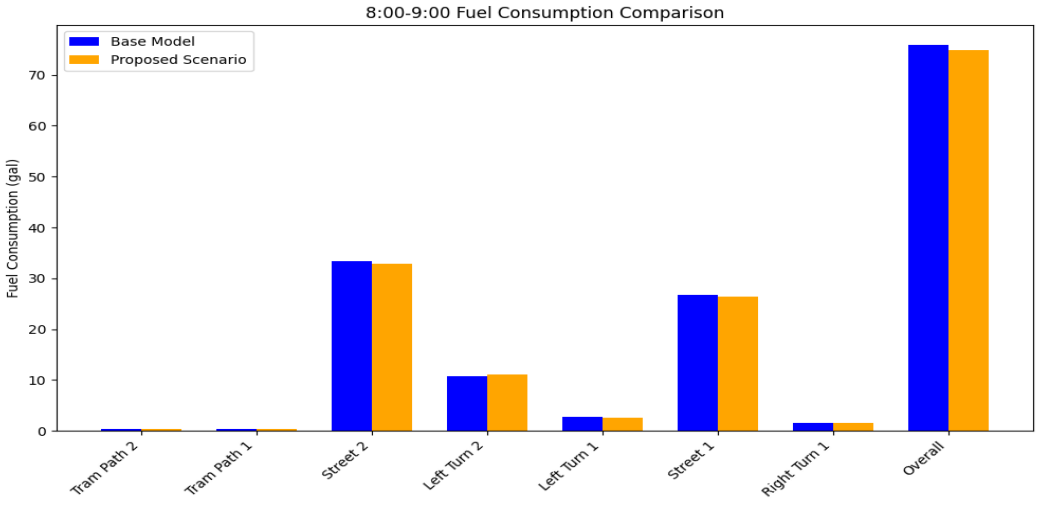


Figure 4. 5 fuel consumption comparison (8:00-9:00)

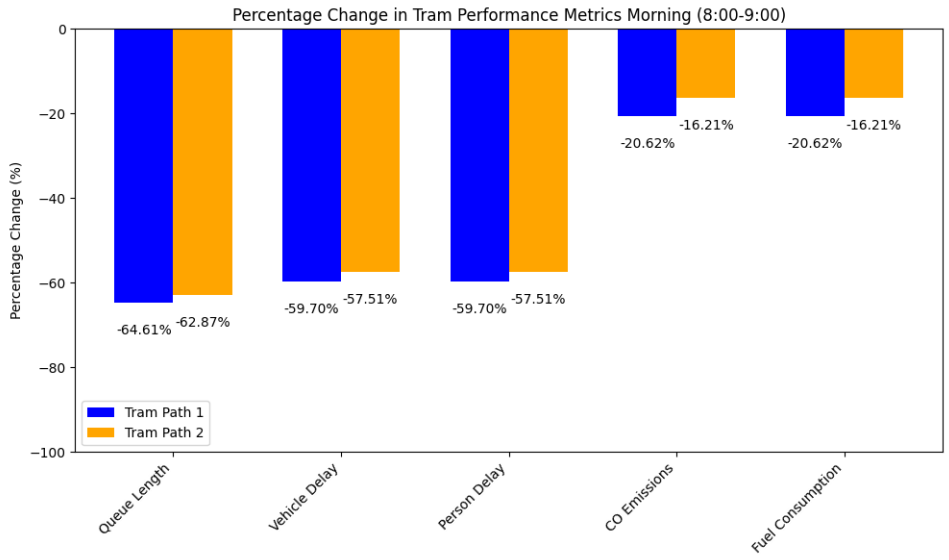


Figure 4. 6 Tram's overall compassion results (8:00-9:00)

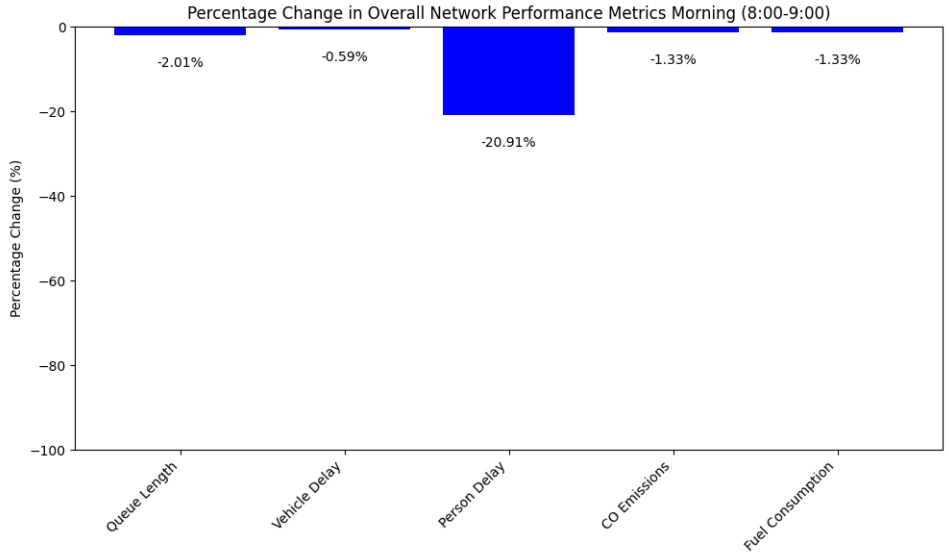


Figure 4. 7 Overall network performance metrics (8:00-9:00)

Table 4. 1 Comparison results (8:00-9:00)

Movement	Queue Length (m)	Vehicle Delay (s/veh)	Person Delay (s/person)	CO Emissions (g)	Fuel Consumption (gal)
Tram Path 2	5.60/2.08 (62.87%)	16.50/7.01 (57.51%)	16.50/7.01 (-57.51%)	28.18/23.61 (16.21%)	0.40/0.34 (16.21%)
Tram Path 1	6.96/2.46 (64.61%)	20.73/8.36 (59.70%)	20.73/8.36 (-59.70%)	29.97/23.79 (20.62%)	0.43/0.34 (20.62%)
Street 2	26.15/28.89 (10.48%)	17.39/17.03 (2.05%)	18.49/18.91 (2.25%)	2334.32/ 2292.29 (-1.80%)	33.40/32.79 (-1.80%)
Left Turn 2	42.39/45.68 (7.78%)	65.21/70.75 (8.50%)	65.85/69.74 (5.91%)	749.58/ 772.52 (3.06%)	10.72/11.05 (3.06%)
Left Turn 1	7.01/7.49 (6.82%)	45.95/47.35 (3.04%)	45.95/47.35 (3.04%)	187.50/ 185.48 (-1.08%)	2.68/2.65 (1.08%)
Street 1	35.95/34.96 (2.76%)	19.89/19.42 (2.32%)	20.84/20.82 (-0.08%)	1872.65/ 1841.35 (-1.67%)	26.79/26.34 (-1.67%)
Right Turn 1	35.95/34.96 (2.76%)	14.40/13.55 (5.91%)	14.40/13.55 (-5.91%)	112.18/ 107.67 (-4.02%)	1.60/1.54 (4.02%)
Overall	20.68/20.26 (2.01%)	23.30/23.16 (0.59%)	19.95/15.78 (-20.91%)	5309.22/ 5238.81 (-1.33%)	75.95/74.95 (-1.33%)

- 12:00–1:00 PM (Midday):

For Tram Paths, the queue lengths for Tram Path 1 decreased by 52.96% (from 3.01 m to 1.41 m) and for Tram Path 2 by 59.62% (from 3.24 m to 1.31 m). While in the best scenario, it was reduced to 0.65 m and 0.81 m, showing excellent tram flow. Vehicle and Person Delay for tram Path 1 delays dropped by 44.88% (from 11.08 s to 6.11 s). Tram Path 2 saw reductions of 50.85% (from 11.57 s to 5.69 s). These improvements have occurred because of the implementation of tram priority.

LOS improved from B to A for both tram paths, showing that tram service quality is excellent in a proposed scenario. Regarding Environmental performance measures, emissions and fuel consumption, CO emissions also decreased, reaching about 10.33% for Tram Path 1 (22.52 g → 20.19 g), and 10.89% for Tram Path 2 (23.09 g → 20.58 g). A similar margin reduced fuel consumption due to shorter tram operating times.

Movement for non-tram paths changed little. The queue length on street 2 was reduced by 6.26% (from 16.37 m to 15.34 m), and delays also improved slightly; for instance, vehicle delay was decreased by 4.55%, and person delays were reduced by 2,73%. In contrast, U-turns and left turns had longer queues (9.80%) and higher delays (e.g., 9.23% for Left Turn 2), indicating some trade-offs. Street 1 and Right Turn 1 saw small reductions in queue length (-4.94%) and delays (-4.22% and -6.73%, respectively).

Regarding overall network performance, the queue length decreased by 6.08% (from 10.99 m to 10.33 m), and the person delay dropped significantly by 18.93% (from 14.6 s to 11.83 s). CO emissions and fuel consumption were reduced by 1.19%, and LOS remained at B, indicating stable network performance with improved tram efficiency. The overall results are shown in Appendix G.

- 5:00–6:00 PM (Evening Peak):

The proposed scenario significantly minimized the queue lengths for the Tram Paths. The queue length for tram path 1 decreased by 90.14% (from 4.11 m to 0.41 m), while that for tram path 2 decreased by 92.43% (from 7.99 m to 0.6 m). While in the best scenario, it was close to almost zero, demonstrating excellent tram flow.

Vehicle and person delays on Tram Path 1 were 89.33% reduced (from 11.56 s to 1.23 s). Tram Path 2 delays decreased by 91.03% (from 20.21 s to 1.81 s). These are the most significant improvements across all periods, reflecting the strategy's effectiveness during peak congestion.

LOS for tram lines was improved from B and C to A for both tram paths. As for Environmental performance measures emissions and fuel consumption, CO emissions were down 21.15% for Tram Path 1 (26.14 g to 20.61 g) and 31.54% for Tram Path 2 (33.50 g to 22.93 g), also Fuel consumption reductions were 21.15% and 31.54%, respectively, due to minimal tram delays.

The impact on non-tram movement was mixed. For instance, the Street 1 queue length is about 4.5% lower; accordingly, the delay changes are more modest by about 3.06 %, indicating improved flow for some other paths. On Street 2, the queue length increased by 0.73% (from 12.95 m to 13.04 m), and the vehicle delay increased by 1.67%. Alternatively, queue length reduction was found to be minor

for U-turns and left turns (- 1.5%), but delay results exhibit more mixed findings (e.g., + 0.54% for the left turn 1, - 0.46% for the left turn 2).

Concerning the network performance overall, the queue length improved by 16.49% (12.44 m → 10.39 m), and the person delay was reduced by as much as 42.49% (15.7 s → 9.03 s); at the same time, vehicle delay decreased by 1.85%. With a 0.47% reduction in CO emissions and fuel consumption, with LOS at B, significant benefits arise for passengers without compromising overall network performance. The overall results are shown in Appendix H.

- Overall Efficiency of the Tram Priority Strategy:

The tram priority strategy consistently improved performance across all periods, with more pronounced improvement at the evening peak (5:00–6:00 PM). Key observations:

Tram Efficiency: When we look for the average of all cases, we find that for Tram Path 1 and Tram Path 2, the average queue lengths are reduced by 69.58% and 76.27%, and the average delays by 63.81%–69.95%, with LOS improving to A. That suggests trams were close to free-flow traffic conditions, which would be suitable for reliability and passenger experience. Environmental Impact: Reducing CO emissions for tram paths by 17.85–20.82% and corresponding fuel consumption decrease in agreement with sustainability goals.

Network Trade-offs: Queues were increased for non-tram movements (for example, Street 2 Straight at 8:00-9:00 increased by 10.48%) and delays at intersections (e.g., U-turns), but for main paths (Street 1, Street 2), metrics were often stable or improved. Network-wide LOS remained stable (B or C) with significant decreases in people delay (18.93–42.49%), showing that trams have better carriage capabilities.

Time-of-Day Variation: The strategy performed best during the evening peak, where tram priority alleviated congestion. Midday was slightly better, while AM Peak was mixed, with modest tram changes balanced by non-tram delays.

Reliability: As shown in the minimum and maximum values (Appendix C to Appendix F), while tram queues were at or near zero in some periods, maximum queues for other movements, e.g., 238 m for Street 2 Straight 8:00–9:00, demonstrated varying peak-time congestion, indicating that time-dependent signal

changes may be needed to alleviate this congestion. The overall results are shown below:

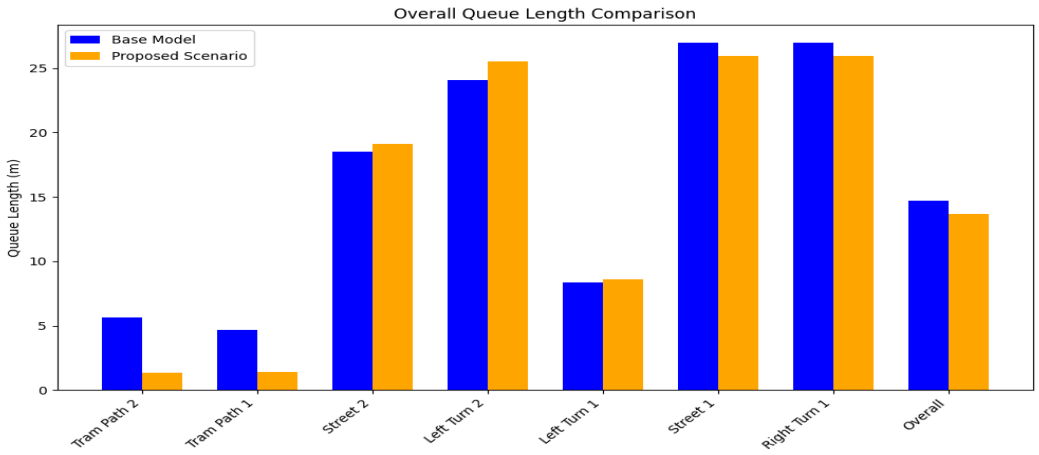


Figure 4. 8 Queue length comparison (overall evaluation)

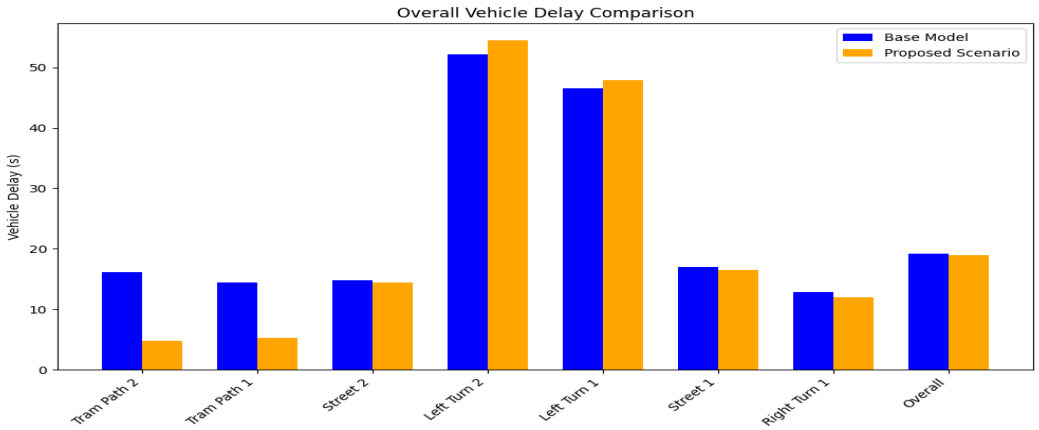


Figure 4. 9 Vehicle delay comparison (overall evaluation)

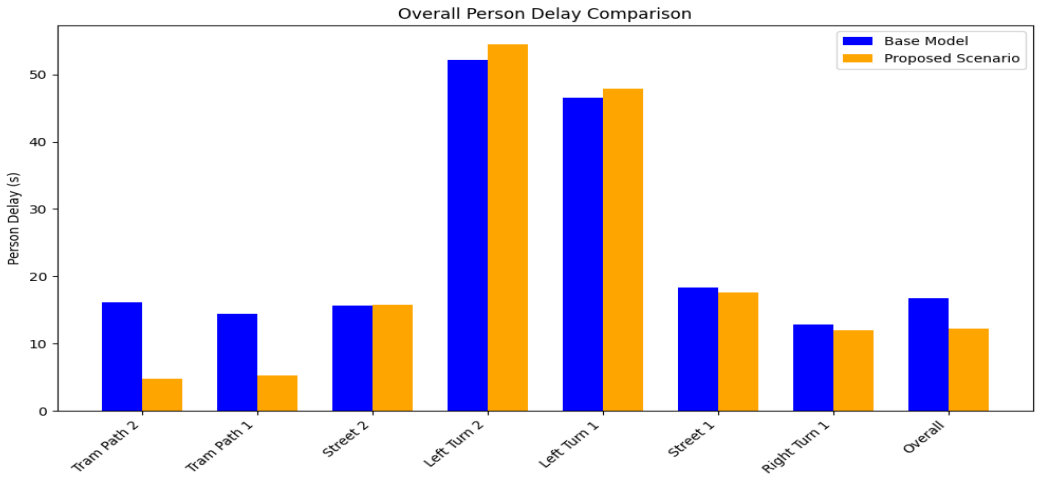


Figure 4. 10 Person delay comparison (overall evaluation)

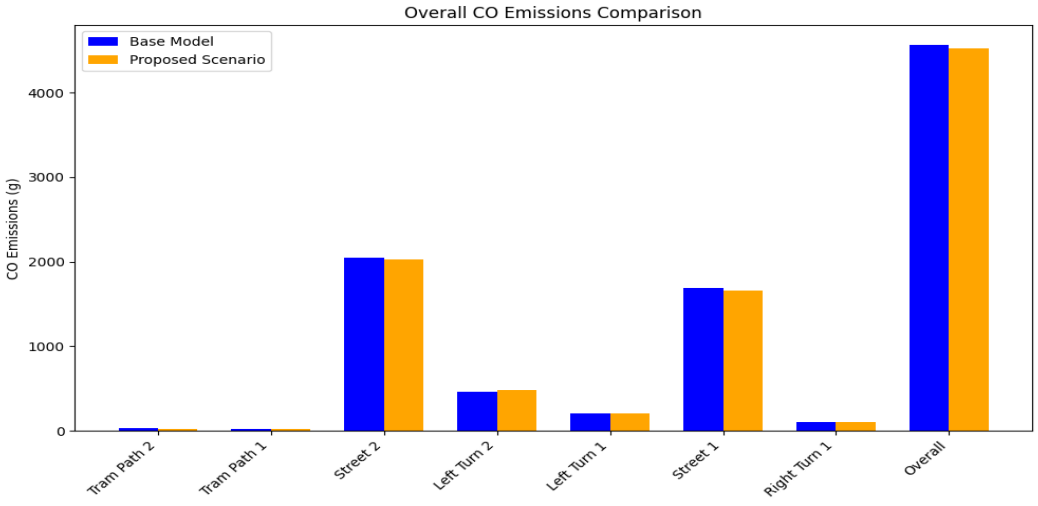


Figure 4. 11 CO emission comparison (overall evaluation)

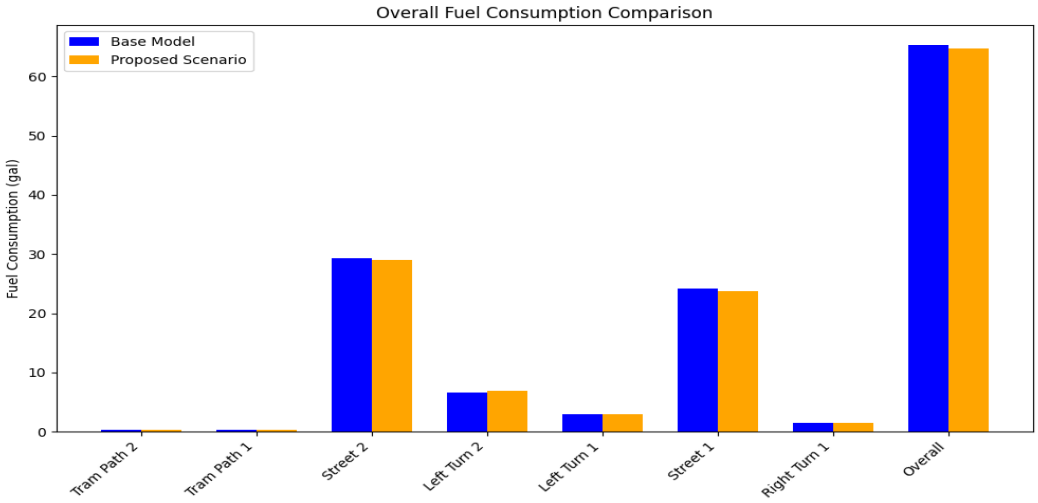


Figure 4. 12 Fuel consumption comparison (overall evaluation)

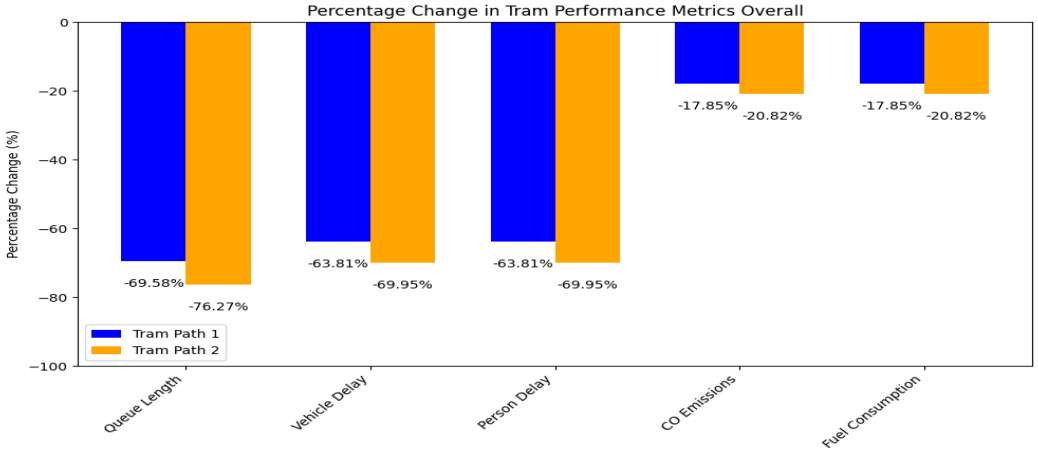


Figure 4. 13 The tram's overall composition results (overall evaluation)

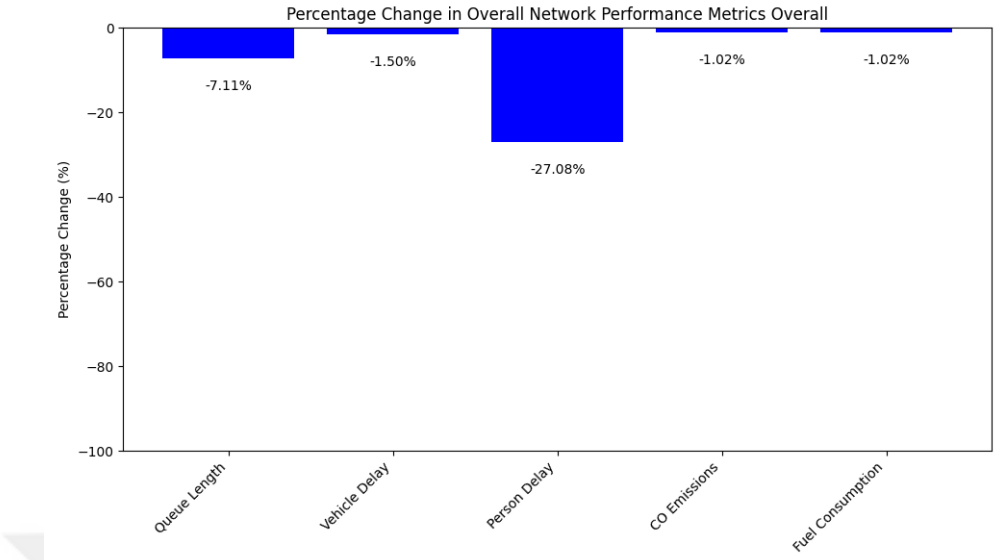


Figure 4. 14 Overall network performance metrics (overall evaluation)

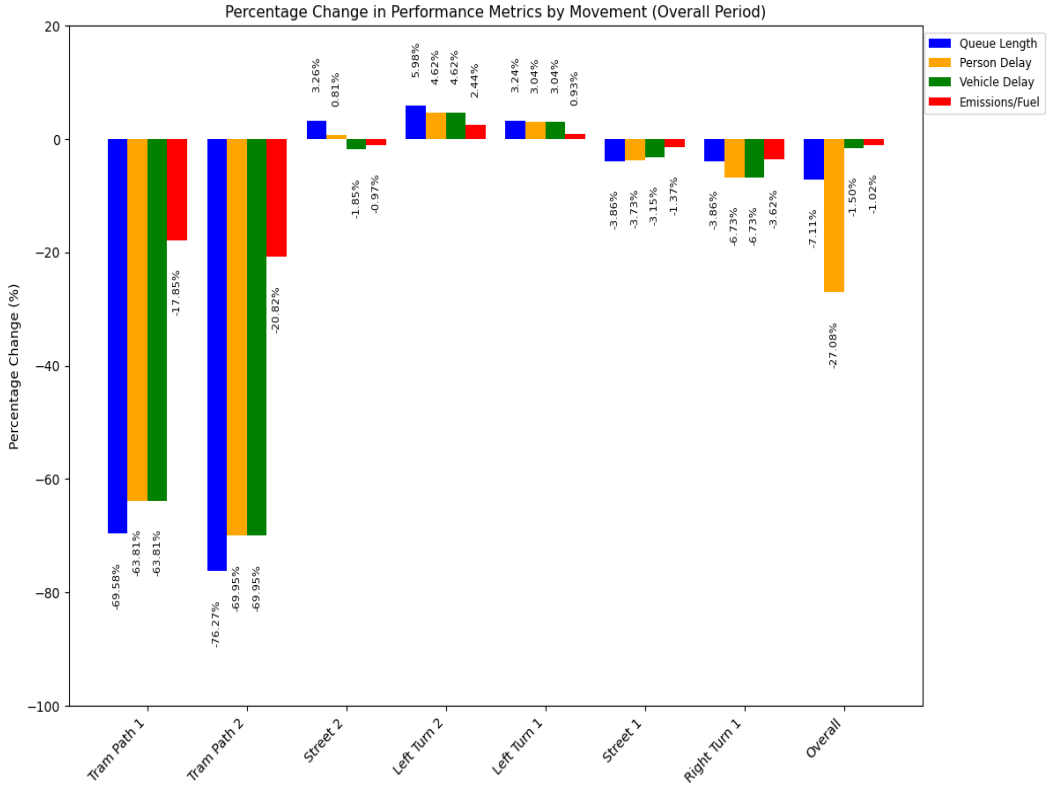


Figure 4. 15 Change in performance metrics by movement (all periods)

Table 4. 2 Overall evaluation results (all periods)

Movement	Queue Length (m)	Vehicle Delay (s/veh)	Person Delay (s/person)	CO Emissions (g)	Fuel Consumption (gal)
Tram Path 2	5.61/1.33 (76.27%)	16.09/4.84 (-69.95%)	16.09/4.84 (-69.95%)	28.26/22.38 (20.82%)	0.40/0.32 (-20.82%)
Tram Path 1	4.69/1.43 (69.58%)	14.46/5.23 (-63.81%)	14.46/5.23 (-63.81%)	26.21/21.53 (17.85%)	0.37/0.31 (-17.85%)
Street 2	18.49/19.09 (3.26%)	14.75/14.48 (-1.85%)	15.61/15.74 (0.81%)	2050.52/2030.6 (-0.97%)	29.34/29.05 (-0.97%)
Left Turn 2	24.09/25.53 (5.98%)	52.11/54.51 (4.62%)	52.11/54.51 (4.62%)	467.65/479.28 (2.49%)	6.69/6.85 (2.39%)
Left Turn 1	8.34/8.61 (3.24%)	46.50/47.92 (3.04%)	46.50/47.92 (3.04%)	208.10/210.02 (0.93%)	2.98/3.00 (0.93%)
Street 1	27.00/25.96 (-3.86%)	17.04/16.51 (-3.15%)	18.34/17.65 (-3.73%)	1686.15/1663.1 (-1.37%)	24.12/23.79 (-1.37%)
Right Turn 1	27.00/25.96 (-3.86%)	12.90/12.04 (-6.73%)	12.90/12.04 (-6.73%)	104.88/101.08 (-3.62%)	1.50/1.45 (-3.62%)
Overall	14.70/13.66 (-7.11%)	19.23/18.94 (-1.50%)	16.75/12.21 (-27.08%)	4567.17/4520.4 (-1.02%)	65.34/64.67 (-1.02%)

4.2 Limitations

Although this study offers valuable insights into the effects of TSP on Turgut Özal Millet Cd, several limitations should be noted to contextualize the results and inform future research. The first limitation is that the dependence on PTV VISSIM and VISVAP, particularly their thesis versions, restricts the detail and realism of some simulations. The academic license also limits the scale of the model; sometimes, this restricts the analysis and limits complete control over the signaling algorithms. Moreover, the software's simplified assumptions about driver behavior and environmental factors may not fully capture the complexities of real-world scenarios, potentially affecting the accuracy of predictions for queue length, delay, and emissions.

Second, the congestion patterns highlighted major issues, especially for non-tram movements. The mean queue lengths of U-turns and left turns in peak time, e.g., a 7.78% increase of Left Turn 2 in 8:00–9:00, show that TSP could result in being slow for different traffic types at individual intersections. Our analysis of these bottlenecks shows that signal priority, as currently implemented, creates an

imbalance in flows between tram and non-tram movement, an area that needs additional investigation.

Third, simulations were only based on 3 days of data, which might not be able to capture the dynamics of traffic conditions at Turgut Özal Millet Cd. Such a small data sample may also provide a limited view of long-term traffic trends. In addition, there were missing data points, including the average number of tram passengers and the average number of bus passengers, which were estimated rather than measured and may have made errors more likely in the person delay and overall performance measures.

Finally, there is still no evidence of the TSP strategy's scalability beyond the studied area. The performance seen in this one intersection with one unique traffic composition may not reflect performance in more extensive, more comprehensive networks, or more diverse regions, such as heavy freight traffic. Thus, the generalizability of the findings is limited and should be further tested in other urban settings to validate the strategy's broader relevance.

4.3 Recommendations

Based on the findings and limitations of this study, the following recommendations are proposed to enhance the implementation of tram signal priority and enhance urban transportation systems in Istanbul and similar cities:

- Policy and Implementation Strategies:

Overall, TSP provides benefits that should be realized wherever appropriate, and primary research requirements suggest that local governments should adopt TSP at key junctions with high tram usage. However, pilot studies are recommended to validate simulation results in a real-world context for successful deployment. These pilots would involve coordination between planners, traffic engineers, and policymakers, taking a participatory approach to enhance TSP strategies into feasible solutions and mitigate potential disturbances, such as vehicle delays. By integrating stakeholder feedback, these initiatives can promote sustainable and equitable integration of TSP into Istanbul's transportation framework.

- Technical Improvements:

To mitigate the impact, technical enhancements to signal timing strategies are necessary to minimize these obvious trade-offs, particularly the additional delays associated with movements such as Left Turn 2. Adaptive signal phasing should be considered for continuous traffic control, where green light times are dynamically adjusted based on real-time traffic conditions, to improve performance for both trams and vehicles. Better detector placement and a more accurate signal control strategy can help maximize TSP activation and avoid unnecessary delays caused by vehicles waiting at intersections. In addition, they would complement the increased capacity for public transport, especially for trams, as they would avoid impacting the overall traffic flow, as demonstrated by the need to reduce the 7.78% queue length at Left Turn 2 during peak hours.

- Future Research Directions:

Further studies may do this by exploring TSPs in a much broader range, including multiple intersections, and thus performing a thorough analysis of network-level impacts. Such would mitigate the scalability limitation by investigating TSP under different traffic compositions and urban types. Additional insights (or even new approaches) about TSP utilization, such as recent AI developments for adaptive signal control, could help make TSP systems more adaptive to congestion patterns in real-time, thereby potentially avoiding increases in TSP queue length. Moreover, investigating the economic impacts and passenger satisfaction associated with TSP will provide a general view of its benefits, informing better policy decisions. Combined with the technical and policy recommendations outlined, these research efforts will support the transition toward balanced, efficient urban transport systems that prioritize public transit while minimizing disruption to other traffic.

By addressing these limitations and following these recommendations, this study lays the groundwork for optimizing tram signal priority, contributing to the broader goal of sustainable urban mobility in Istanbul and beyond.

4.4 Conclusion

This study aimed to analyze the effectiveness of the transit signal priority (TSP) in Turgut Özal Millet Cd, Istanbul, a central road where tram and automobile

crossings intersect. The analysis compared a base model with a proposed TSP across key performance metrics: queue length, vehicle delay, person delay, CO emissions, and fuel consumption, using comprehensive simulations (carried out with PTV VISSIM and VISVAP). The results show that TSP improves tram efficiency significantly, indicated by the vehicle and person delay reduction (63.81% for tram path 1 and 69.95% for tram path 2) with a decrease in queue lengths up to 76.27%, thereby improving service reliability and passenger satisfaction. Environmental benefits were also evident, with CO emissions and fuel consumption decreasing by up to 17.85% and 20.82% for tram paths, underscoring TSP's potential to support Istanbul's sustainability goals.

However, these improvements came at the cost of longer delays and queues for some vehicular movements: For instance, Left Turn 2 faced up to 7.8% longer queues during peak hours. These results underscore the necessity for a balanced approach to traffic management that minimizes negative consequences for non-transit users. The overall evaluation revealed significant system-wide improvements, with a 20.91% decrease in person delay and a modest reduction in fuel consumption and CO emission (1.33%), vehicle delay (0.6%), and queue length (2.01%), encouraging TSP's role in optimizing urban mobility.

There are two implications of this research. First, it serves as an empirical basis on which transportation planners can argue for implementing TSP in Istanbul, especially in tram-dominated paths, to improve public transit efficiency and environmental performance. Second, it emphasizes the need for complementary measures, such as adaptive signal timing or intersection redesign, to address vehicle delays. While there are limitations, Such as the limitations of the simulation software and the difficulty of collecting and processing data, this study sets the stage for future exploration of multi-modal TSP strategies and real-world pilot programs. The TSP system is a feasible way for sustainable urban mobility advancement in Istanbul. TSP positions itself to reduce tram delays and emissions while balancing the operating complexities of mixed traffic, which has become a trend worldwide as we move towards transit-oriented development. The prioritized research and actions provide a template and call to action to drive further practice and policy change, using the significant co-benefits of improved public transport to address the urgent and compounding risks of inaction.

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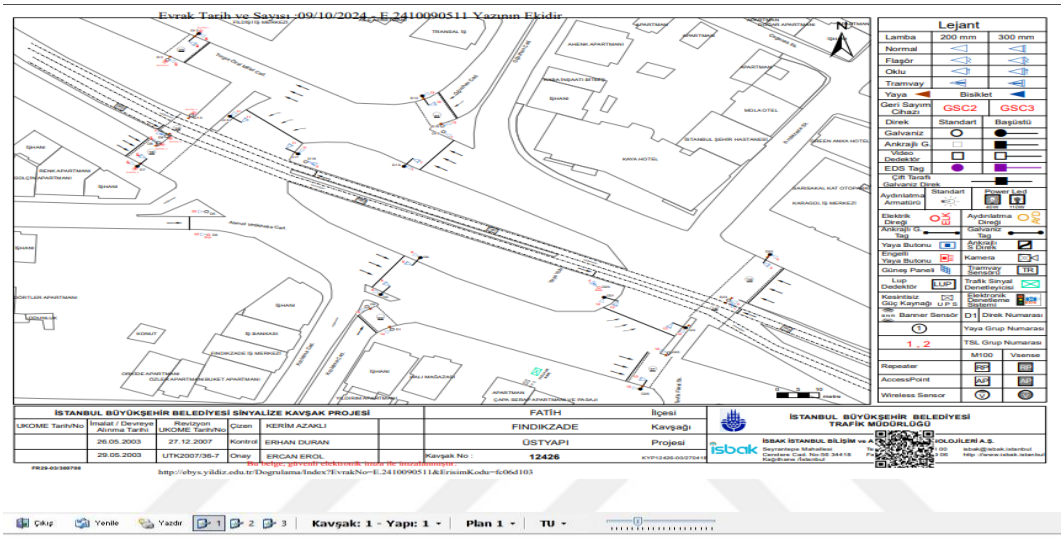
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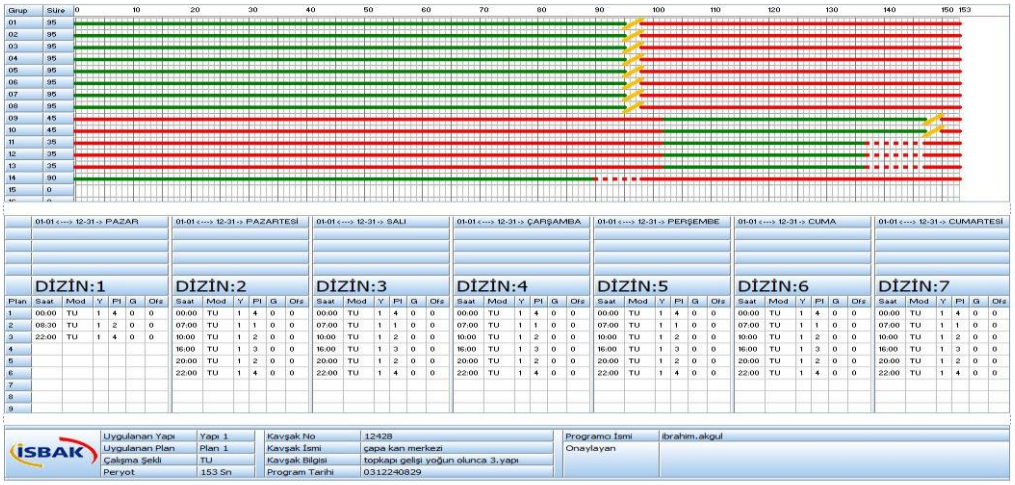
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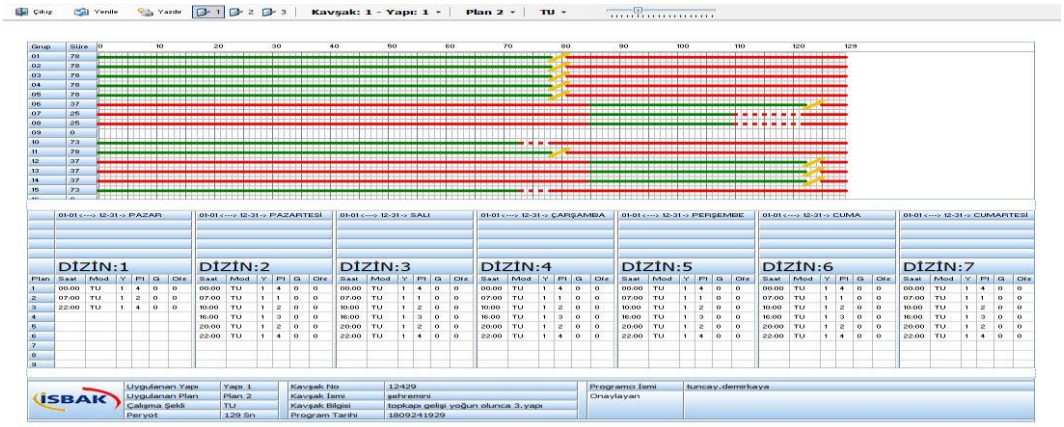
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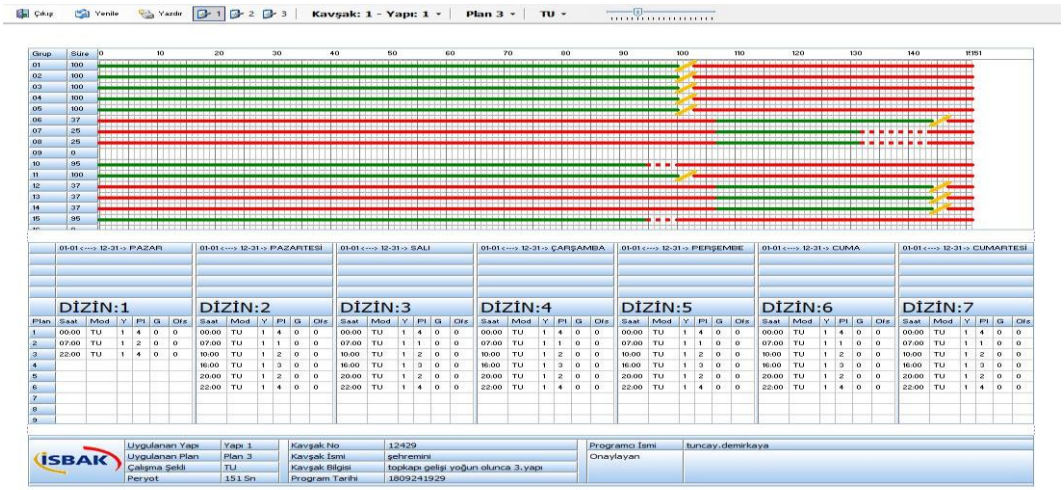
A
APPENDICES

Appendix A: Intersection information









Appendix B: Traffic volume data

From 8:00-9:00 (E to W)

Time	private cars (straight)	private cars (turning left)	private cars(turning right)	public buses	trucks	Motorcycle	pedestrians	Tram
0-10	204	23	27	17	5	16	30	6
10-20	251	10	12	18	4	11	29	4
20-30	216	15	18	17	3	17	57	4
30-40	222	17	24	18	7	11	39	4
40-50	238	17	18	23	5	14	47	3
50-60	197	18	20	12	5	16	46	4

From 8:00-9:00 (W to E)

Time	private cars (straight)	private cars (turning left)	public buses	trucks	Motorcycle	pedestrians	tram
0-10	248	59	23	4	25	92	3
10-20	222	45	12	11	35	62	5
20-30	224	63	21	6	40	101	3
30-40	242	65	12	2	33	77	6
40-50	255	52	26	10	34	46	5
50-60	250	55	20	1	39	65	5

From 12:00-13:00 (E to W)

Time	private cars (straight)	private cars (turning left)	private cars (turning right)	public buses	trucks	Motorcycle	pedestrians	tram
0-10	196	15	15	13	5	24	61	4
10-20	194	17	10	14	7	16	68	4
20-30	184	16	17	14	4	21	75	4
30-40	171	19	12	14	5	31	79	4
40-50	187	16	22	12	5	32	77	4
50-60	204	17	12	11	8	26	102	4

From 12:00-13:00 (W to E)

Time	private cars (straight)	private cars (turning left)	public buses	trucks	Motorcycle	pedestrians	tram
0-10	225	31	9	14	25	83	4
10-20	198	34	15	8	41	81	4
20-30	190	28	15	14	32	108	4
30-40	182	33	11	9	43	80	4
40-50	256	35	15	11	50	77	4
50-60	199	38	12	5	41	89	4

From 17:00-18:00 (E to W)

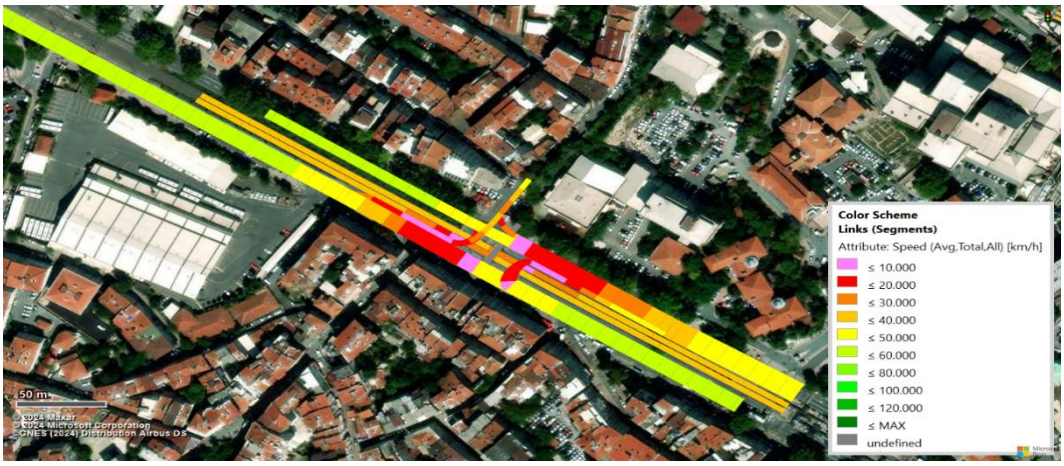
time	private cars (straight)	private cars (turning left)	private cars(turning right)	public buses	trucks	Motorcycle	pedestrians	tram
0-10	176	15	28	15	3	37	81	5
10_20	211	20	17	18	5	52	78	4
20-30	183	18	23	14	4	48	87	5
30-40	189	17	23	11	4	44	64	5
40-50	177	22	20	12	8	35	73	4
50-60	186	24	21	15	5	42	77	5

From 17:00-18:00 (W to E)

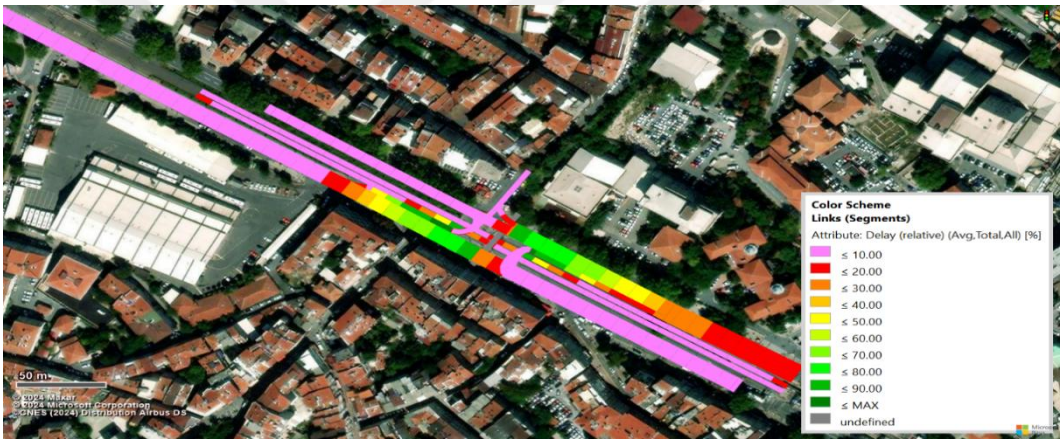
time	private cars (straight)	private cars (turning left)	public buses	trucks	Motorcycle	pedestrians	tram	total
0-10	218	33	15	5	42	109	5	318
10_20	234	32	22	4	48	98	5	345
20-30	184	28	13	7	28	73	5	265
30-40	171	31	17	6	35	84	5	265
40-50	210	31	17	5	44	102	5	312
50-60	203	30	18	7	52	113	5	315

Appendix C: Second case (12:00 - 13:00) base model results:

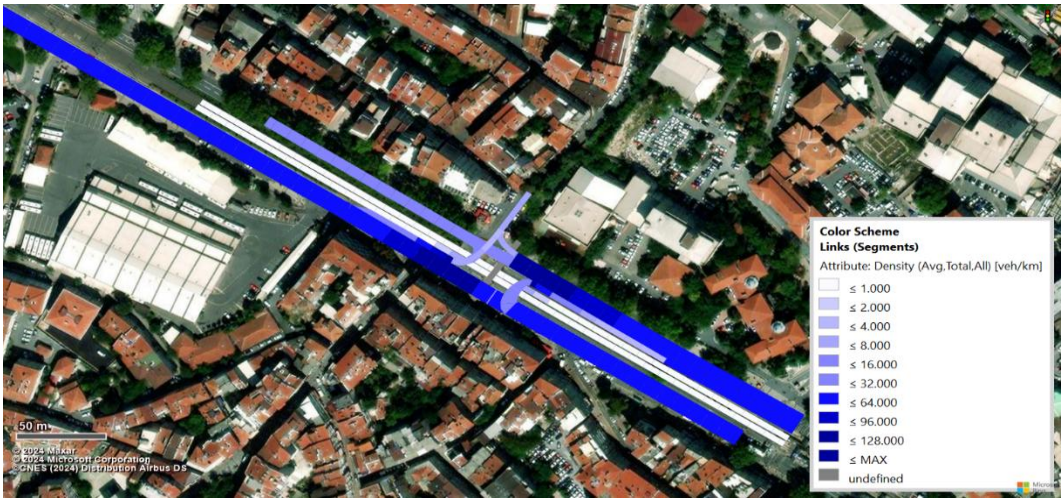
Speed



Relative delay



Density



Total results

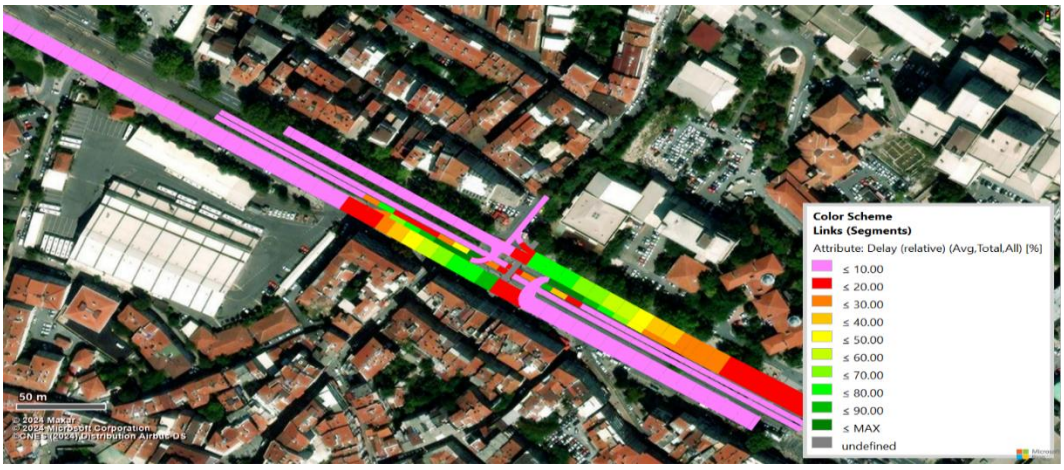
Sim	Time int.	Movement	Q length	Q length max	n.of Veh	n.of Person	LOS	Veh delay	Person delay	Stopped delay	Stops	Emiss CO	EmissNOx	Emiss vox	Fuel cons.
Average	900-4800	Tram Path 2	3.24287	62.429966	24	4800	2	11.5713	11.571331	7.134597	0.32917	23.094441	4.493339	5.35236	0.330393
Average	900-4800	Tram Path 1	3.00719	62.405532	24	4800	2	11.0794	11.079405	6.457508	0.3375	22.518636	4.381308	5.218911	0.322155
Average	900-4800	Street 2	16.367	118.70275	1780	5726	2	14.6871	15.194793	9.717783	0.48573	1995.53	388.2576	462.4833	28.548355
Average	900-4800	Left Turn 2	13.029	80.839415	109	109	4	38.6893	38.689322	32.097624	0.76334	168.98166	32.87769	39.16313	2.417477
Average	900-4800	U turn 2	13.029	80.839415	108	108	4	38.635	38.63503	32.489357	0.76956	150.08167	29.20044	34.78288	2.147091
Average	900-4800	Left Turn 1	6.17544	48.485579	118	118	4	38.9563	38.956311	30.650761	0.74878	173.50657	33.75807	40.21182	2.482211
Average	900-4800	Street 1	24.1441	161.26724	1507	5783	2	16.6484	18.129391	10.595821	0.51685	1599.4261	311.1902	370.6824	22.881632
Average	900-4800	Right Turn 1	24.1441	161.26724	110	110	2	12.7772	12.777167	8.745778	0.40283	84.001939	16.34373	19.46826	1.201744
Average	900-4800	Overall	10.9943	161.26724	3779	21554	2	17.5134	14.595556	11.955619	0.5184	4212.1953	819.5402	976.2169	60.260305
Minimum	900-4800	Tram Path 2	1.99558	62.30335	24	4800	1	7.82739	7.82739	4.202472	0.25	21.417063	4.166982	4.963611	0.306396
Minimum	900-4800	Tram Path 1	1.84186	62.265771	24	4800	1	8.16435	8.164347	3.324162	0.25	21.317767	4.147663	4.940598	0.304975
Minimum	900-4800	Street 2	14.6726	99.438292	1683	5223	2	13.9973	12.142984	9.107252	0.45845	1898.3427	369.3485	439.9593	27.157978
Minimum	900-4800	Left Turn 2	10.3884	64.96533	86	86	3	34.9219	34.921929	28.417128	0.7094	128.13533	24.93048	29.6966	1.833123
Minimum	900-4800	U turn 2	10.3884	64.96533	95	95	4	35.8914	35.891445	30.108231	0.66346	135.08566	26.28276	31.30741	1.932556
Minimum	900-4800	Left Turn 1	4.27601	35.570528	90	90	4	35.1934	35.193408	28.119005	0.65421	124.71445	24.2649	28.90378	1.784184
Minimum	900-4800	Street 1	22.0315	142.49554	1444	5083	2	15.5491	14.881596	9.828378	0.47776	1510.9283	293.9717	350.1722	21.615569
Minimum	900-4800	Right Turn 1	22.0315	142.49554	95	95	2	10.0719	10.071917	6.444268	0.33913	70.049423	13.62907	16.23463	1.002138
Minimum	900-4800	Overall	10.5567	142.49554	3672	20565	2	17.0332	13.593761	11.655356	0.49428	4036.9359	785.441	935.5989	57.753018
Maximum	900-4800	Tram Path 2	3.84775	62.531997	24	4800	2	13.1904	13.190436	8.793302	0.375	23.823429	4.635174	5.52131	0.340822
Maximum	900-4800	Tram Path 1	4.6002	62.64061	24	4800	2	16.1824	16.182442	10.174055	0.45833	24.836305	4.832242	5.756053	0.355312
Maximum	900-4800	Street 2	17.5329	139.99801	1821	6377	2	15.3218	17.472911	10.250569	0.51126	2079.553	404.6054	481.9565	29.7504
Maximum	900-4800	Left Turn 2	16.2398	105.14903	121	121	4	43.0755	43.075501	36.869065	0.80342	186.9071	36.36533	43.31753	2.673921
Maximum	900-4800	U turn 2	16.2398	105.14903	119	119	4	44.318	44.318035	37.506204	0.85714	180.41138	35.1015	41.81208	2.580993
Maximum	900-4800	Left Turn 1	7.55219	65.414644	140	140	4	41.1904	41.190408	32.817039	0.82677	203.80635	39.65331	47.23409	2.915685
Maximum	900-4800	Street 1	27.8399	192.26829	1561	6527	2	18.1953	22.968742	11.530229	0.5924	1737.0092	337.9589	402.5687	24.849917
Maximum	900-4800	Right Turn 1	27.8399	192.26829	128	128	2	14.927	14.926954	10.138756	0.46094	105.46778	20.5202	24.44318	1.508838
Maximum	900-4800	Overall	11.6089	192.26829	3855	22015	2	18.0342	15.795841	12.371027	0.55231	4301.0545	836.8289	996.8109	61.531538

Appendix D: Third case (17:00 - 18:00) base model results:

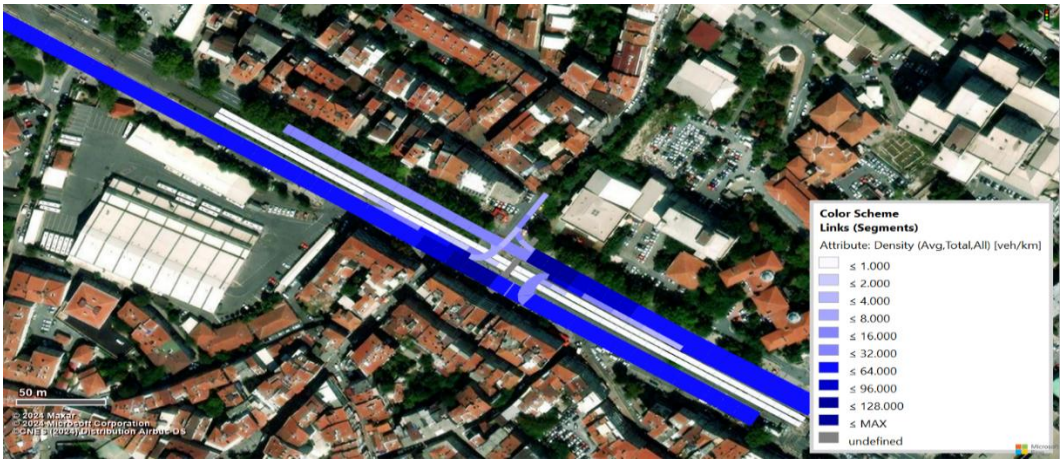
Speed



Relative delay



Density

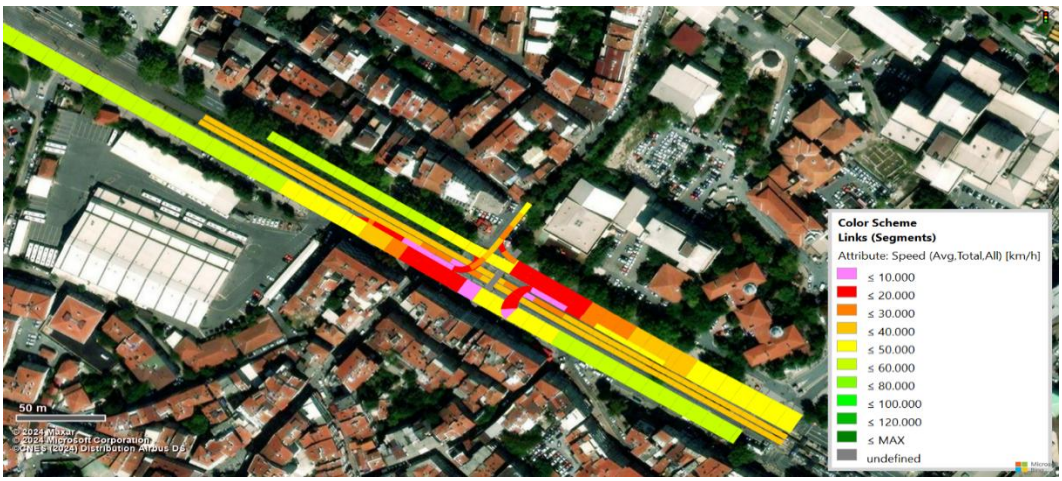


Total results

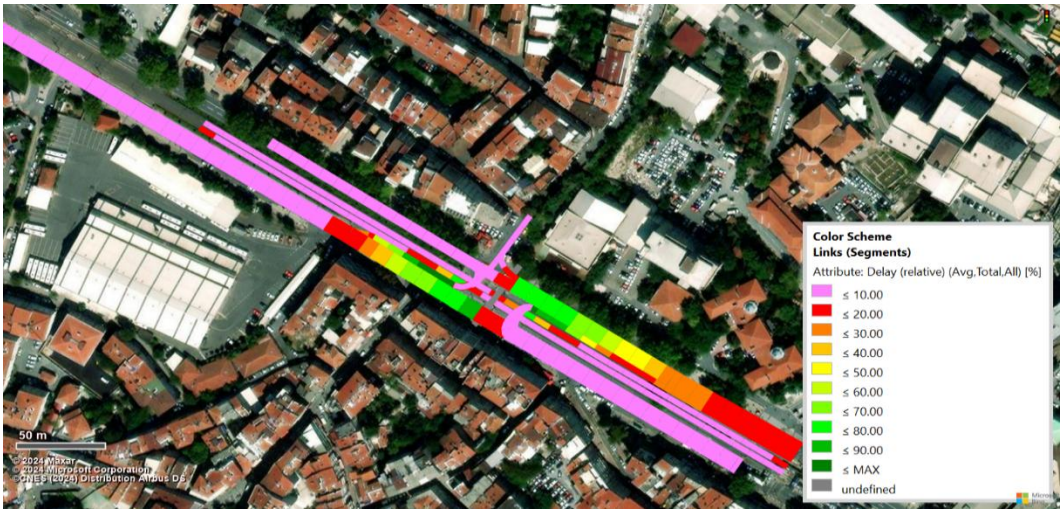
Sim	Time int.	Movement	Q length	Q length max	n.of Veh	n.of Person	LOS	Veh delay	Person delay	Stopped delay	Stops	Emiss CO	EmissNOx	Emiss vox	Fuel cons.
Average	900-4800	Tram Path 2	7.98831	123.96441	30	6000	3	20.2106	20.21061	14.038186	0.49	33.4988	6.51765	7.76368	0.479239
Average	900-4800	Tram Path 1	4.11276	62.357319	28	5600	2	11.56	11.559992	8.192215	0.27857	26.1438	5.08663	6.05908	0.374017
Average	900-4800	Street 2 Straight	12.9451	107.0611	1749	7302	2	12.1772	13.147821	7.996044	0.3919	1821.71	354.439	422.199	26.061658
Average	900-4800	From 2 to 1 (U-turn)	16.8614	90.296939	98	98	4	52.8467	52.846718	45.960675	0.80344	172.324	33.528	39.9378	2.465294
Average	900-4800	From 2 to 1 Left Turn	16.8614	90.296939	102	102	4	50.7553	50.75527	44.102172	0.81628	161.996	31.5186	37.5442	2.317543
Average	900-4800	From 1 to 2 (U-turn)	11.8484	68.709454	152	152	5	54.6021	54.602124	44.020612	0.83938	263.277	51.2241	61.0169	3.766478
Average	900-4800	Street 1 Straight	20.9086	159.63977	1569	6219	2	14.595	16.047271	8.973623	0.47193	1586.38	308.653	367.66	22.69504
Average	900-4800	Street 1 Right Turn	20.9086	159.63977	164	164	2	11.5337	11.533651	7.636347	0.347	118.457	23.0474	27.4535	1.694663
Average	900-4800	All Paths	12.4441	160.32644	3891	25637	2	16.8733	15.700864	11.729462	0.46119	4180.08	813.292	968.774	59.80086
Minimum	900-4800	Tram Path 2	6.89107	123.72262	30	6000	2	17.4811	17.481081	11.932457	0.43333	31.9334	6.21307	7.40086	0.456843
Minimum	900-4800	Tram Path 1	1.61559	62.10268	28	5600	1	5.02297	5.022965	2.8869	0.14286	23.064	4.48741	5.3453	0.329957
Minimum	900-4800	Street 2 Straight	11.5461	85.539662	1705	6689	2	11.2531	11.194708	7.322666	0.37419	1753.63	341.192	406.42	25.087648
Minimum	900-4800	From 2 to 1 (U-turn)	15.0644	62.709993	86	86	4	47.4042	47.404215	41.123327	0.75258	143.803	27.9788	33.3276	2.057262
Minimum	900-4800	From 2 to 1 Left Turn	15.0644	62.709993	86	86	4	45.8283	45.82831	39.630067	0.75728	146.957	28.5925	34.0587	2.102387
Minimum	900-4800	From 1 to 2 (U-turn)	10.3474	46.307905	138	138	4	50.4263	50.426298	39.627614	0.77922	235.603	45.8398	54.6033	3.370574
Minimum	900-4800	Street 1 Straight	18.2346	121.54859	1489	5717	2	13.5823	14.773333	8.249144	0.4427	1489.05	289.716	345.103	21.302633
Minimum	900-4800	Street 1 Right Turn	18.2346	121.54859	145	145	1	9.11227	9.112274	5.725846	0.28947	100.52	19.5575	23.2964	1.438052
Minimum	900-4800	All Paths	11.6117	123.84682	3841	24636	2	15.9783	13.624052	10.774551	0.44494	4102.56	798.209	950.808	58.691844
Maximum	900-4800	Tram Path 2	9.75107	124.34201	30	6000	3	24.197	24.197011	17.083343	0.56667	35.6558	6.93732	8.26357	0.510097
Maximum	900-4800	Tram Path 1	5.42515	62.529376	28	5600	2	15.2271	15.227064	10.872009	0.35714	28.0114	5.44999	6.4919	0.400735
Maximum	900-4800	Street 2 Straight	14.9262	151.10424	1777	7966	2	13.1642	15.532335	8.754126	0.41274	1883.85	366.528	436.599	26.950585
Maximum	900-4800	From 2 to 1 (U-turn)	19.5425	120.96573	111	111	5	59.8335	59.833503	52.02457	0.89216	200.033	38.9192	46.3596	2.861706
Maximum	900-4800	From 2 to 1 Left Turn	19.5425	120.96573	126	126	5	57.4816	57.481551	49.746854	0.87209	203.497	39.593	47.1623	2.911253
Maximum	900-4800	From 1 to 2 (U-turn)	14.3488	105.07973	165	165	5	60.3467	60.346681	49.830321	0.91515	295.233	57.4416	68.4231	4.223647
Maximum	900-4800	Street 1 Straight	23.4467	192.6944	1654	6913	2	16.0513	17.288101	9.76863	0.53079	1667.73	324.479	386.512	23.858781
Maximum	900-4800	Street 1 Right Turn	23.4467	192.6944	183	183	2	13.7798	13.779835	9.688562	0.42759	135.349	26.334	31.3684	1.936324
Maximum	900-4800	All Paths	13.0531	192.6944	3988	26393	2	17.393	17.156538	12.156559	0.48875	4239.24	824.803	982.486	60.647277

Appendix E: Second case (12:00 - 13:00) proposed scenario results:

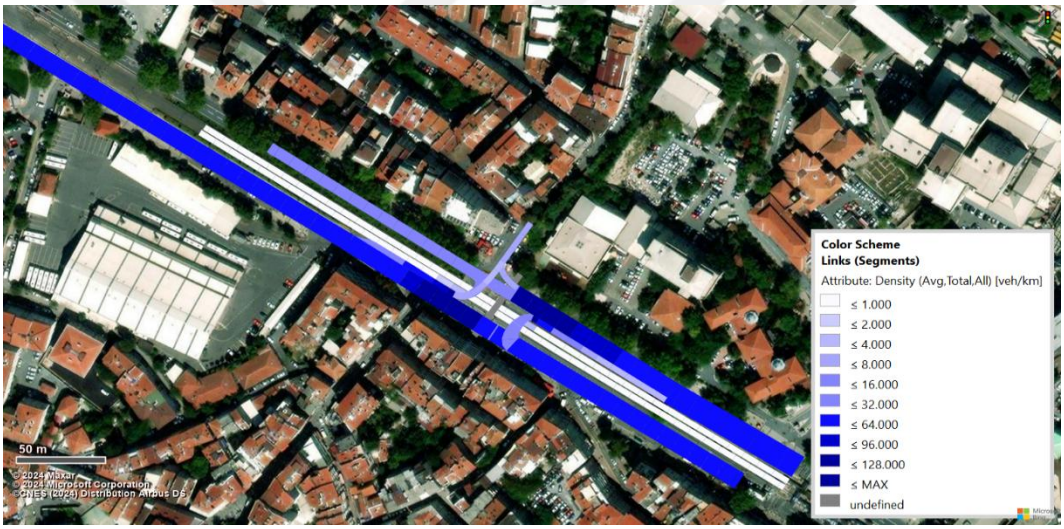
Speed



Relative delay



Density

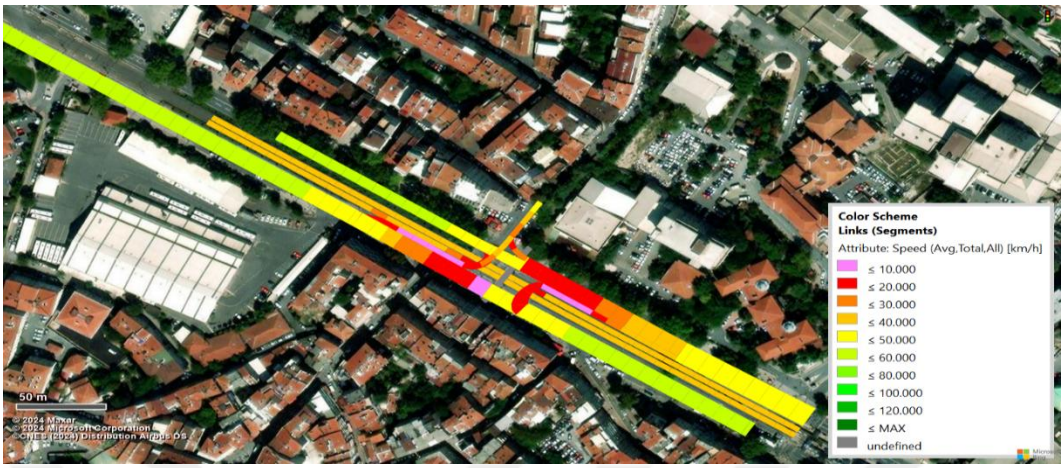


Total results

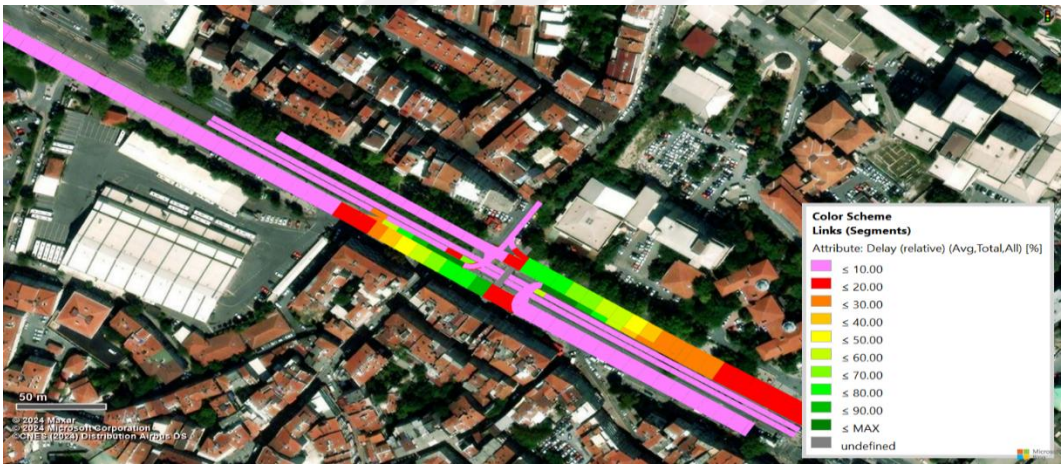
Sim	Time int.	Movement	Q length	Q length max	n.of Veh	n.of Person	LOS	Veh delay	Person delay	Stopped delay	Stops	Emiss CO	EmissNOx	Emiss vox	Fuel cons.
Average	900-4800	Tram Path 2	1.30958	62.402462	24	4800	1	5.6876	5.6876	2.400931	0.225	20.580468	4.004211	4.769722	0.294427
Average	900-4800	Tram Path 1	1.41468	62.358641	24	4800	1	6.10663	6.106632	2.734045	0.20833	20.1924	3.928707	4.679784	0.288876
Average	900-4800	Street 2	15.3427	113.0598	1784	5757	2	14.0187	14.779401	9.309558	0.4523	1955.6991	380.508	453.2522	27.978528
Average	900-4800	Left Turn 2	14.3053	80.351205	109	109	4	41.7834	41.783407	35.072482	0.77537	173.19882	33.6982	40.1405	2.477809
Average	900-4800	U turn 2	14.3053	80.351205	108	108	4	42.6798	42.679756	36.392865	0.77955	156.95993	30.5387	36.37698	2.245493
Average	900-4800	Left Turn 1	6.62896	44.642378	118	118	4	41.5132	41.51317	33.118365	0.75372	177.6243	34.55923	41.16615	2.54112
Average	900-4800	Street 1	22.9515	157.67168	1511	5803	2	15.9455	16.978553	10.058526	0.50821	1583.0559	308.0052	366.8885	22.647438
Average	900-4800	Right Turn 1	22.9515	157.67168	110	110	2	11.9177	11.917691	8.187571	0.36468	80.673755	15.69618	18.69692	1.154131
Average	900-4800	Overall	10.3255	157.67168	3787	21603	2	17.0941	11.832504	11.740048	0.49718	4161.9401	809.7623	964.5698	59.541346
Minimum	900-4800	Tram Path 2	0.8131	62.346726	24	4800	1	3.59547	3.595471	1.391113	0.16667	19.531565	3.800133	4.526629	0.279422
Minimum	900-4800	Tram Path 1	0.6514	62.086456	24	4800	1	3.33194	3.331936	1.273425	0.08333	18.609598	3.620751	4.312954	0.266232
Minimum	900-4800	Street 2	14.1891	91.144451	1707	5225	2	12.8786	12.527284	8.303999	0.42645	1877.6847	365.3292	435.1716	26.862442
Minimum	900-4800	Left Turn 2	12.0968	62.639552	86	86	4	35.6715	35.671542	28.948614	0.71667	141.37981	27.50737	32.76614	2.022601
Minimum	900-4800	U turn 2	12.0968	62.639552	95	95	4	37.8474	37.847406	32.304701	0.71963	144.83414	28.17946	33.56671	2.072019
Minimum	900-4800	Left Turn 1	5.09805	33.153265	90	90	4	37.8937	37.893731	29.71604	0.66387	134.35384	26.14037	31.1378	1.922086
Minimum	900-4800	Street 1	19.4651	136.34182	1449	5095	2	14.3871	14.920329	9.033513	0.47826	1465.4386	285.1211	339.6296	20.964787
Minimum	900-4800	Right Turn 1	19.4651	136.34182	95	95	1	7.97317	7.973165	4.696173	0.25217	66.71196	12.97972	15.46114	0.954391
Minimum	900-4800	Overall	9.72045	136.34182	3673	20601	2	16.3424	10.587358	11.138987	0.474	3962.29	770.9177	918.299	56.685122
Maximum	900-4800	Tram Path 2	1.92584	62.471594	24	4800	1	8.03574	8.035735	3.792018	0.375	22.13142	4.30597	5.12917	0.316615
Maximum	900-4800	Tram Path 1	2.49324	62.554812	24	4800	2	10.3448	10.344839	4.990415	0.33333	22.25662	4.330329	5.158187	0.318407
Maximum	900-4800	Street 2	16.6601	147.07352	1821	6378	2	15.0733	16.549999	10.149991	0.48448	2017.0699	392.4485	467.4754	28.856508
Maximum	900-4800	Left Turn 2	16.302	108.97177	120	120	4	48.7105	48.710482	41.851012	0.83721	198.12832	38.54857	45.91815	2.834454
Maximum	900-4800	U turn 2	16.302	108.97177	119	119	4	49.3447	49.3447	42.591198	0.84034	174.51077	33.95346	40.44456	2.496578
Maximum	900-4800	Left Turn 1	8.59908	59.268992	138	138	4	46.0393	46.039348	37.235358	0.86957	214.92701	41.81699	49.81141	3.074778
Maximum	900-4800	Street 1	25.0756	190.97694	1573	6577	2	17.2027	18.926218	10.911095	0.5508	1698.0053	330.3701	393.5291	24.291922
Maximum	900-4800	Right Turn 1	25.0756	190.97694	127	127	2	15.5352	15.535208	10.976604	0.43396	101.26116	19.70174	23.46825	1.448657
Maximum	900-4800	Overall	10.9084	190.97694	3857	22118	2	18.0649	13.088829	12.423319	0.53521	4286.7838	834.0523	993.5035	61.327378

Appendix F :Third case (17:00 - 18:00) proposed scenario results

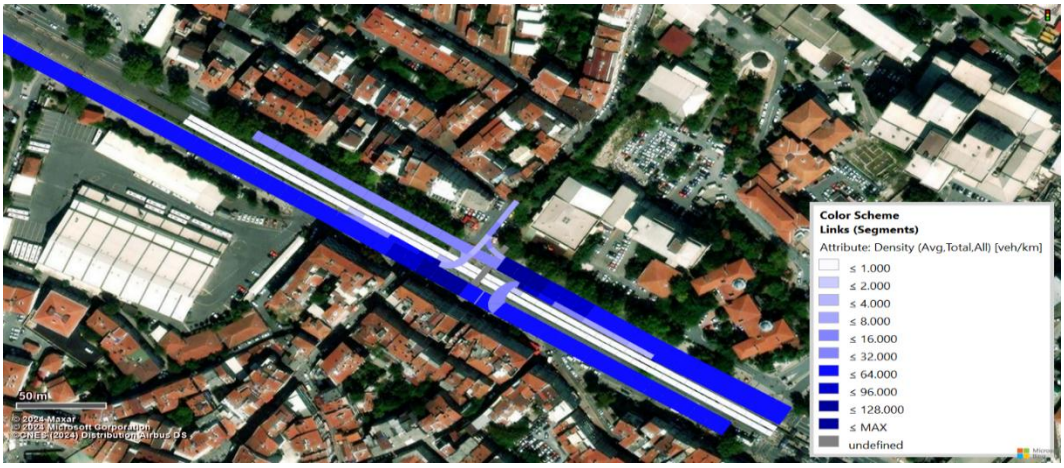
Speed



Relative Delay



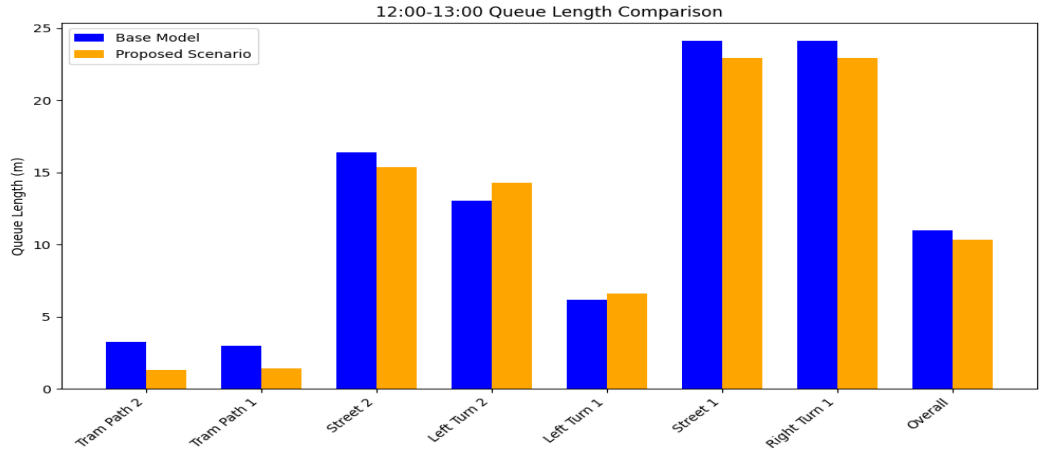
Density

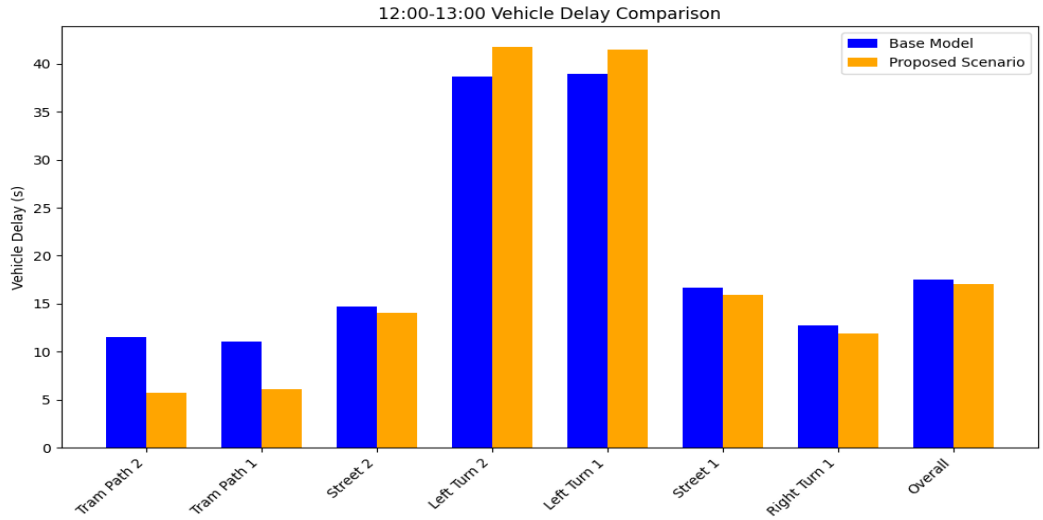


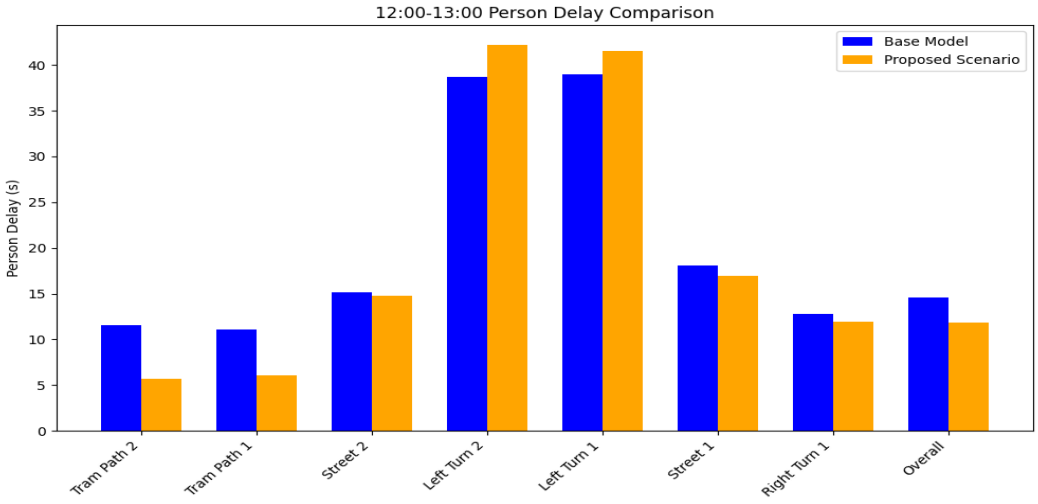
Total results

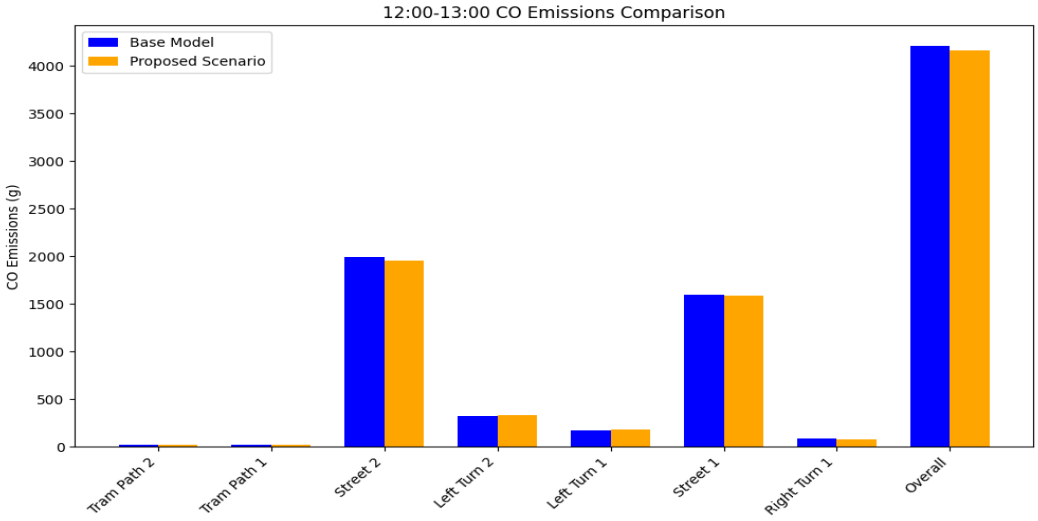
Sim	Time int.	Movement	Q length	Q length max	n.of Veh	n.of Person	LOS	Veh delay	Person delay	Stopped delay	Stops	Emiss CO	EmissNOx	Emiss vox	Fuel cons.
Average	900-4800	Tram Path 2	0.60451	55.89429	30	6000	1	1.81292	1.812921	1.046037	0.04667	22.9327	4.46186	5.31487	0.328078
Average	900-4800	Tram Path 1	0.40572	49.708574	28	5600	1	1.23296	1.232964	0.802009	0.02857	20.6136	4.01066	4.7774	0.294901
Average	900-4800	Street 2 Straight	13.0399	114.39131	1753	7316	2	12.381	13.525207	8.112883	0.40757	1843.82	358.74	427.323	26.377951
Average	900-4800	From 2 to 1 (U-turn)	16.608	91.836839	98	98	4	51.3167	51.316657	44.48266	0.80311	170.353	33.1444	39.4809	2.437091
Average	900-4800	From 2 to 1 Left Turn	16.608	91.836839	103	103	4	51.808	51.808013	45.232351	0.80552	164.803	32.0646	38.1946	2.357692
Average	900-4800	From 1 to 2 (U-turn)	11.728	67.83172	154	154	5	54.8945	54.894502	44.132791	0.83633	266.964	51.9416	61.8716	3.819232
Average	900-4800	Street 1 Straight	19.9682	155.74369	1573	6229	2	14.1482	15.160522	8.662909	0.44947	1564.82	304.457	362.662	22.386516
Average	900-4800	Street 1 Right Turn	19.9682	155.74369	165	165	2	10.6379	10.637879	6.963856	0.32112	114.915	22.3582	26.6326	1.643987
Average	900-4800	All Paths	10.3924	157.43018	3903	25664	2	16.5614	9.029572	11.497356	0.45297	4160.3	809.444	964.19	59.517929
Minimum	900-4800	Tram Path 2	0	0	30	6000	1	0.15491	0.154905	0	0	21.7888	4.23931	5.04976	0.311714
Minimum	900-4800	Tram Path 1	0	0	28	5600	1	0.02864	0.028635	0	0	19.904	3.8726	4.61295	0.28475
Minimum	900-4800	Street 2 Straight	11.6998	78.150544	1710	6693	2	11.4822	11.328532	7.400446	0.37931	1771.72	344.712	410.613	25.3465
Minimum	900-4800	From 2 to 1 (U-turn)	15.0324	65.247587	87	87	4	46.0009	46.000927	39.247626	0.73913	150.359	29.2544	34.8472	2.151061
Minimum	900-4800	From 2 to 1 Left Turn	15.0324	65.247587	85	85	4	44.6166	44.616616	38.641771	0.71875	136.983	26.6519	31.7471	1.959698
Minimum	900-4800	From 1 to 2 (U-turn)	9.50126	50.77629	137	137	4	48.3808	48.380788	37.930302	0.7764	225.965	43.9646	52.3696	3.232691
Minimum	900-4800	Street 1 Straight	17.1085	114.9385	1492	5740	2	12.8995	12.964342	7.78159	0.40415	1435.99	279.391	332.804	20.543455
Minimum	900-4800	Street 1 Right Turn	17.1085	114.9385	145	145	1	9.47473	9.474734	5.810399	0.27586	96.2655	18.7298	22.3105	1.377188
Minimum	900-4800	All Paths	9.56315	119.68199	3848	24643	2	15.7174	8.008531	10.908842	0.42251	4021.39	782.417	931.996	57.530635
Maximum	900-4800	Tram Path 2	1.8028	124.03844	30	6000	1	4.96519	4.965186	3.244379	0.13333	24.7486	4.81517	5.73572	0.354057
Maximum	900-4800	Tram Path 1	0.67855	62.467087	28	5600	1	2.05664	2.056636	1.401071	0.03571	21.0565	4.09682	4.88004	0.301237
Maximum	900-4800	Street 2 Straight	14.7841	152.82901	1781	7969	2	13.1823	15.936274	8.767131	0.444	1910.94	371.799	442.878	27.338171
Maximum	900-4800	From 2 to 1 (U-turn)	18.4326	138.9738	111	111	5	56.5188	56.518807	49.963502	0.85567	198.152	38.5532	45.9237	2.834795
Maximum	900-4800	From 2 to 1 Left Turn	18.4326	138.9738	126	126	5	58.0859	58.085908	52.025184	0.90476	213.044	41.4506	49.375	3.04784
Maximum	900-4800	From 1 to 2 (U-turn)	16.7393	96.922233	166	166	5	66.7208	66.72083	54.135855	0.94578	324.328	63.1025	75.1662	4.639888
Maximum	900-4800	Street 1 Straight	23.1003	180.3668	1656	6916	2	15.587	20.401015	9.673322	0.51055	1703.32	331.404	394.761	24.367958
Maximum	900-4800	Street 1 Right Turn	23.1003	180.3668	184	184	2	12.1399	12.139924	8.475124	0.34615	127.581	24.8226	29.5682	1.825195
Maximum	900-4800	All Paths	11.0355	180.3668	3994	26403	2	17.0279	10.513957	11.899543	0.47191	4295.93	835.831	995.622	61.458165

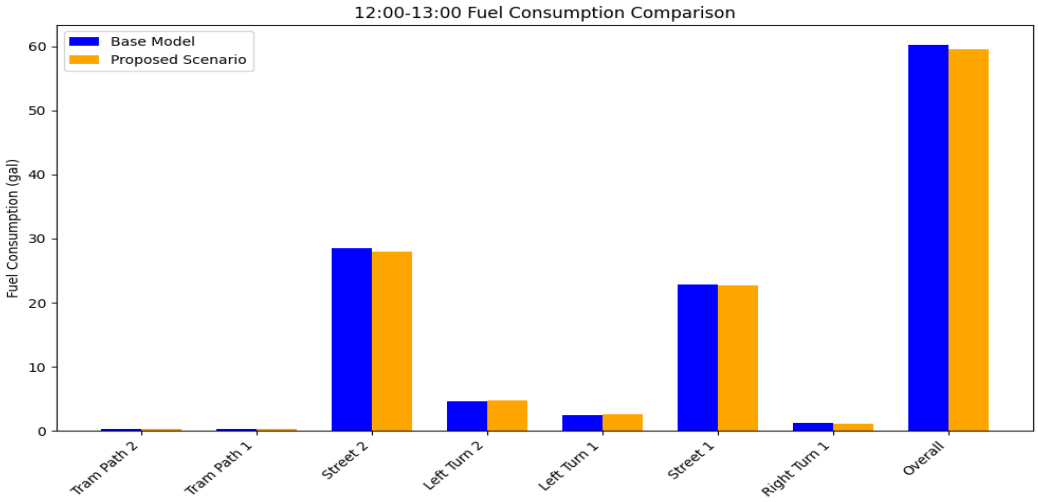
Appendix G: Second case comparison results:

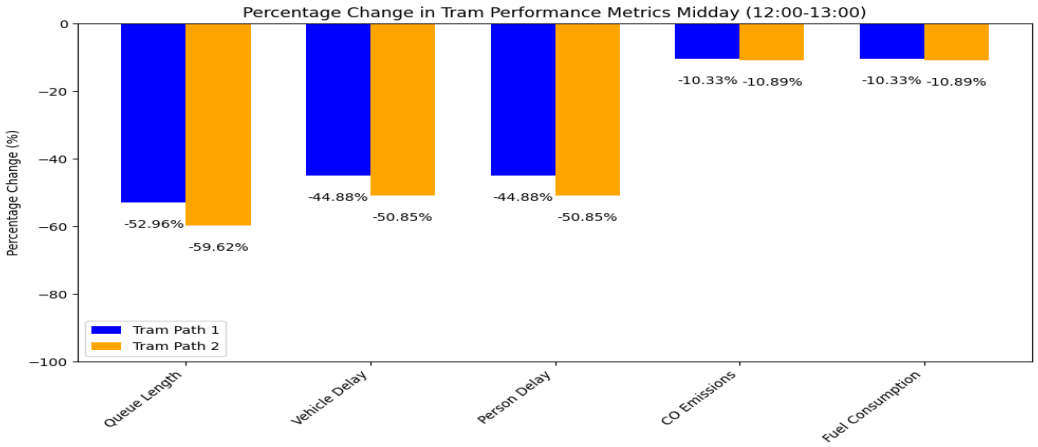


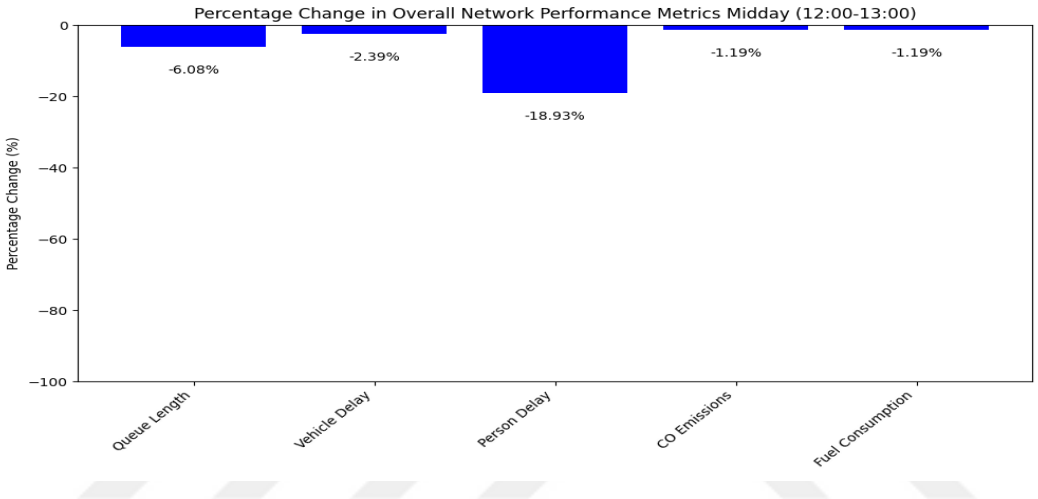



12:00-13:00 Person Delay Comparison
Base Model
Proposed Scenario
Person Delay (s)
0
5
10
15
20
25
30
35
40
Tram Path 2
Tram Path 1
Street 2
Left Turn 2
Left Turn 1
Street 1
Right Turn 1
Overall


12:00-13:00 CO Emissions Comparison
Base Model
Proposed Scenario
CO Emissions (g)
0
500
1000
1500
2000
2500
3000
3500
4000
Tram Path 2
Tram Path 1
Street 2
Left Turn 2
Left Turn 1
Street 1
Right Turn 1
Overall

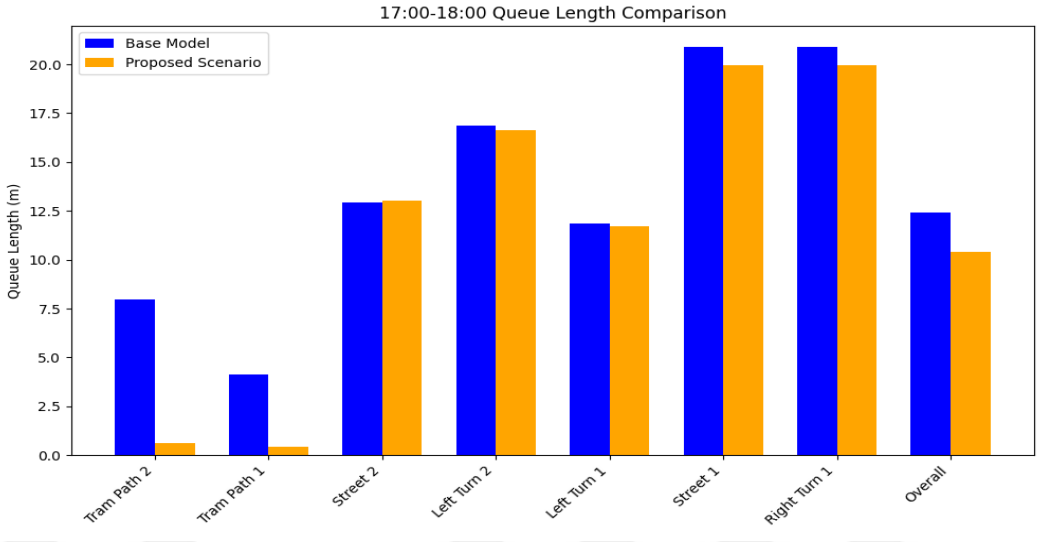

12:00-13:00 Fuel Consumption Comparison
Base Model
Proposed Scenario
Fuel Consumption (gal)
0
10
20
30
40
50
60
Tram Path 2
Tram Path 1
Street 2
Left Turn 2
Left Turn 1
Street 1
Right Turn 1
Overall

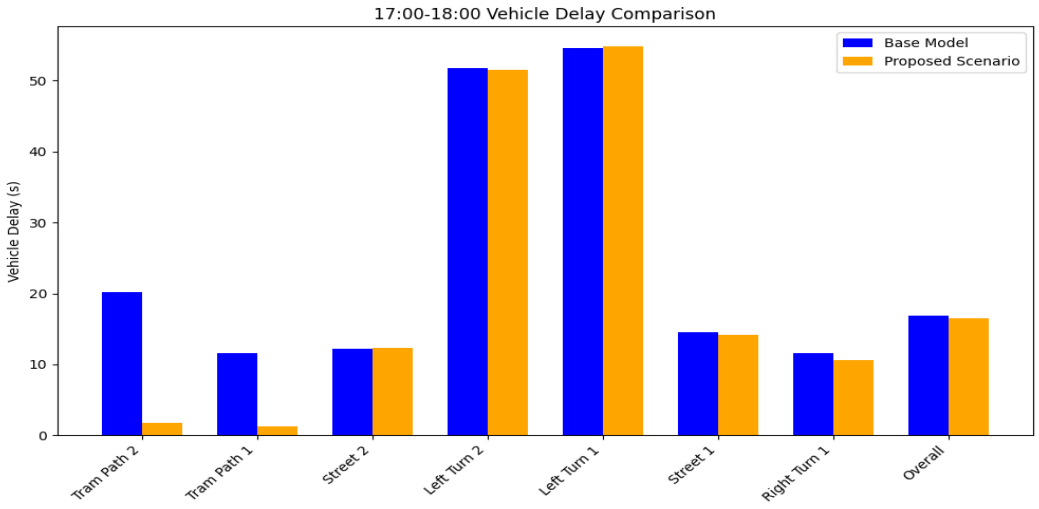


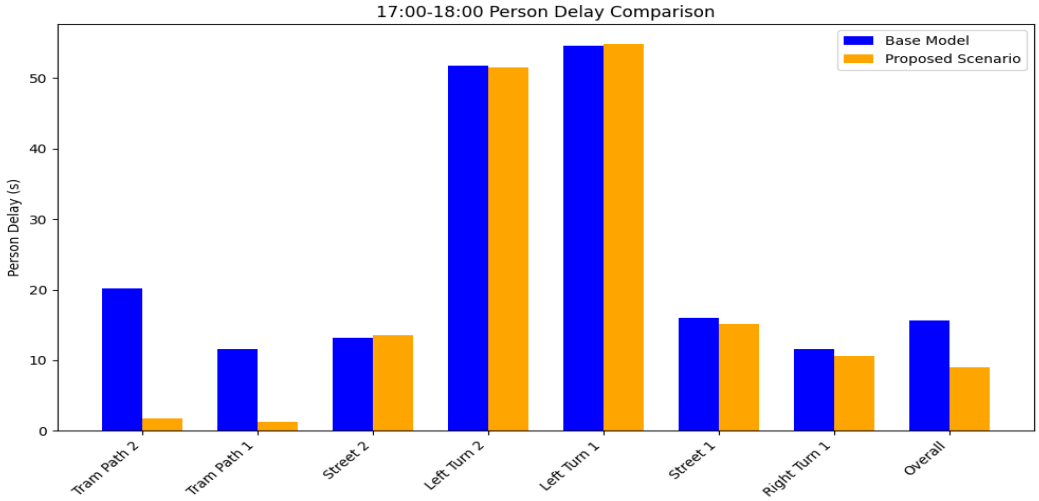


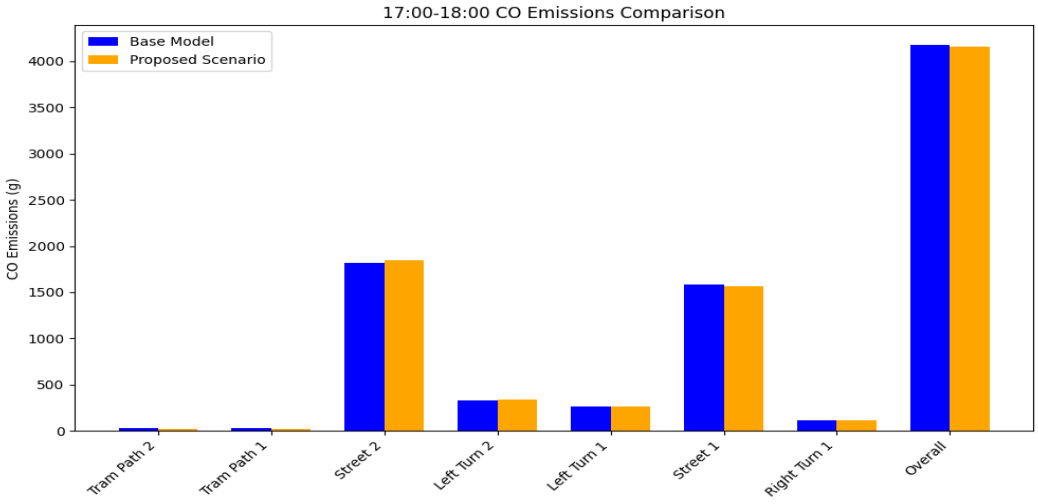
Movement	Queue Length (m)	Vehicle Delay (s/veh)	Person Delay (s/person)	CO Emissions (g)	Fuel Consumption (gal)
Tram Path 2	3.24/1.31 (59.62%)	11.57/5.69 (-50.85%)	11.57/5.69 (-50.85%)	23.09/20.58 (10.89%)	0.33/0.29 (10.89%)
Tram Path 1	3.01/1.41 (52.96%)	11.08/6.11 (-44.88%)	11.08/6.11 (-44.88%)	22.52/20.19 (10.33%)	0.32/0.29 (10.33%)
Street 2	16.37/15.34 (-6.26%)	14.69/14.02 (-4.55%)	15.19/14.78 (-2.73%)	1995.53/ 1955.70 (2.00%)	28.55/27.98 (-2.00%)
Left Turn 2	13.03/14.31 (9.80%)	38.66/42.23 (9.23%)	38.66/42.23 (9.23%)	319.06/330. 16 (3.48%)	4.56/4.72 (3.48%)
Left Turn 1	6.18/6.63 (7.34%)	38.96/41.51 (6.56%)	38.96/41.51 (6.56%)	173.51/177. 62 (2.37%)	2.48/2.54 (2.37%)
Street 1	24.14/22.95 (-4.94%)	16.65/15.95 (-4.22%)	18.13/16.98 (-6.35%)	1599.43/ 1583.06 (1.02%)	22.88/22.65 (-1.02%)
Right Turn 1	24.14/22.95 (-4.94%)	12.78/11.92 (-6.73%)	12.78/11.92 (-6.73%)	84.00/80.67 (3.96%)	1.20/1.15 (3.96%)
Overall	10.99/10.33 (-6.08%)	17.51/17.09 (-2.39%)	14.60/11.83 (18.93%)	4212.20/ 4161.94 (1.19%)	60.26/59.54 (-1.19%)

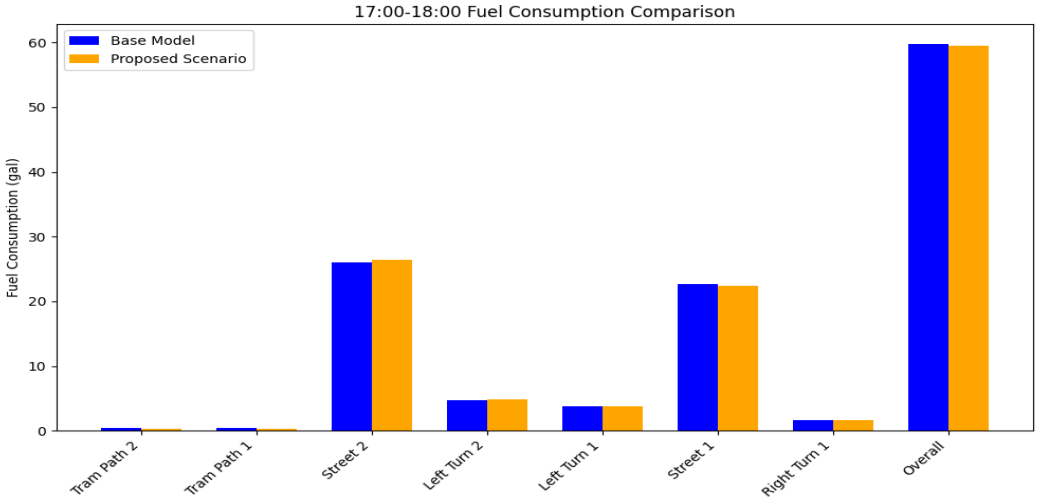
Appendix H :Third Case comparison results:

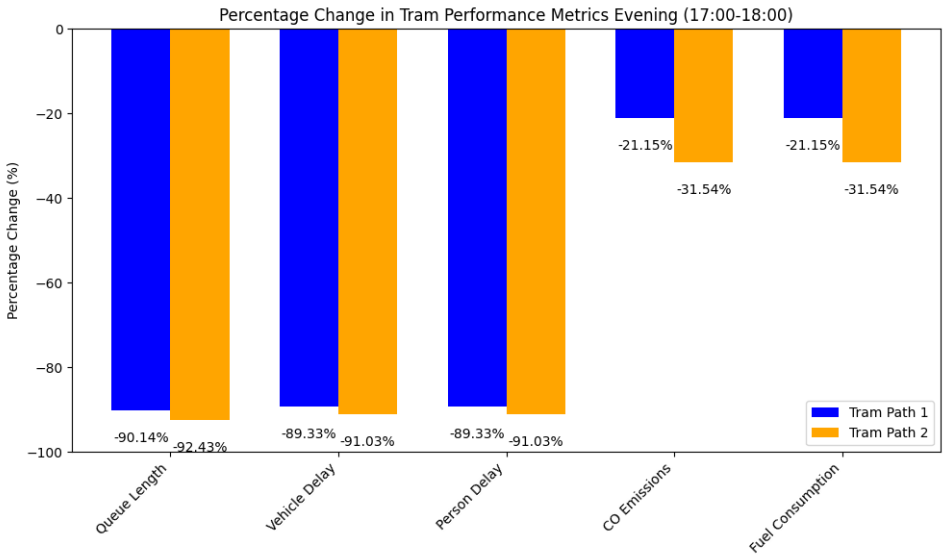


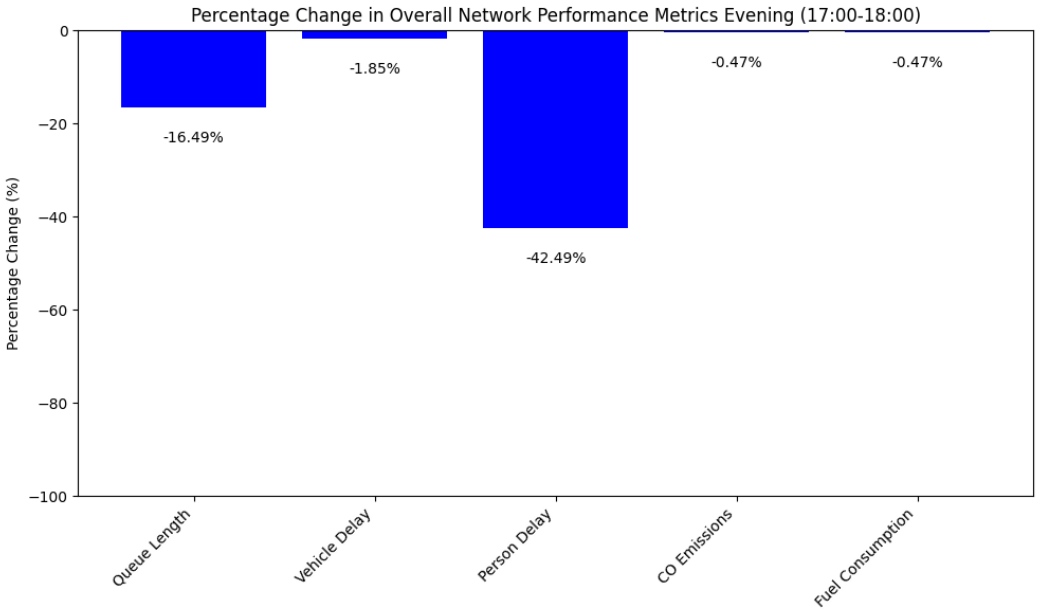





17:00-18:00 CO Emissions Comparison
Base Model
Proposed Scenario
CO Emissions (g)
0
500
1000
1500
2000
2500
3000
3500
4000
Tram Path 2
Tram Path 1
Street 2
Left Turn 2
Left Turn 1
Street 1
Right Turn 1
Overall


17:00-18:00 Fuel Consumption Comparison
Base Model
Proposed Scenario
Fuel Consumption (gal)
0
10
20
30
40
50
60
Tram Path 2
Tram Path 1
Street 2
Left Turn 2
Left Turn 1
Street 1
Right Turn 1
Overall


Percentage Change in Tram Performance Metrics Evening (17:00-18:00)
Percentage Change (%)
0
−20
−40
−60
−80
−100
-90.14%
-92.43%
-89.33%
-91.03%
-89.33%
-91.03%
-21.15%
-31.54%
-21.15%
-31.54%
Tram Path 1
Tram Path 2
Queue Length
Vehicle Delay
Person Delay
CO Emissions
Fuel Consumption



Movement	Queue Length (m)	Vehicle Delay (s/veh)	Person Delay (s/person)	CO Emissions (g)	Fuel Consumption (gal)
Tram Path 2	7.99/0.60 (92.43%)	20.21/1.81 (-91.03%)	20.21/1.81 (-91.03%)	33.50/22.93 (31.54%)	0.48/0.33 (31.54%)
Tram Path 1	4.11/0.41 (90.14%)	11.56/1.23 (-89.33%)	11.56/1.23 (-89.33%)	26.14/20.61 (21.15%)	0.37/0.29 (21.15%)
Street 2	12.95/13.04 (0.73%)	12.18/12.38 (1.67%)	13.15/13.53 (2.87%)	1821.71/ 1843.82 (1.21%)	26.06/26.38 (1.21%)
Left Turn 2	16.86/16.61 (-1.50%)	51.80/51.56 (-0.46%)	51.80/51.56 (-0.46%)	334.32/ 335.16 (0.25%)	4.78/4.79 (0.25%)
Left Turn 1	11.85/11.73 (-1.02%)	54.60/54.89 (0.54%)	54.60/54.89 (0.54%)	263.28/ 266.96 (1.40%)	3.77/3.82 (1.40%)
Street 1	20.91/19.97 (-4.50%)	14.59/14.15 (-3.06%)	16.05/15.16 (-5.53%)	1586.38/ 1564.82 (1.36%)	22.70/22.39 (-1.36%)
Right Turn 1	20.91/19.97 (-4.50%)	11.53/10.64 (-7.77%)	11.53/10.64 (-7.77%)	118.46/ 114.91 (2.99%)	1.69/1.64 (2.99%)
Overall	12.44/10.39 (-16.49%)	16.87/16.56 (-1.85%)	15.70/9.03 (-42.49%)	4180.08/ 4160.30 (0.47%)	59.80/59.52 (-0.47%)

Appendix I: Report on Queue Length Definition and Calculation in PTV VISSIM

Introduction

This report addresses the definition and calculation of queue length in PTV VISSIM, as used in my thesis to evaluate Transit Signal Priority (TSP) strategies. The focus is on tram queue length, reported as 5.6 meters in the 8:00–9:00 base scenario, despite the tram length being about 60 meters. This report defines queue length, explains how VISSIM calculates it, and provides a simple example to clarify the process for tram queues.

Definition of Queue Length in PTV VISSIM

In PTV VISSIM, queue length is a key performance metric that quantifies the spatial extent of trams waiting at a designated point, such as a signalized intersection's stop line.

Queue Length: The distance from the stop line to the rear of the last tram that is either stopped or moving below a defined speed threshold (typically 3–5 km/h).

Description mentioned in the program: Average queue length[m]: The current queue length is measured in each time step, and the arithmetic mean is thus calculated per time interval.

Context in Thesis: For the T1 tram line, queue length measures the average extent of tram queues at the intersection, reflecting delays caused by traffic signals. In the base scenario (8:00– 9:00), the average tram queue length is 5.6 meters, indicating minimal queuing despite the tram's 60-meter length.

Queue length is averaged over the simulation period (1 hour) and is used to assess intersection performance and the effectiveness of TSP strategies, which reduced tram queue lengths to 1.33–1.43 meters (LOS A) from 5.6 meters (LOS C/B).

Calculation of Queue Length in PTV VISSIM

PTV VISSIM calculates queue length using queue counters placed at specific locations (e.g., the intersection's stop line). The process involves:

Queue Detection: VISSIM identifies vehicles or trams as part of a queue if they are stopped or moving below a speed threshold (e.g., 3 km/h)

Measurement: The queue counter records the distance from the stop line to the rear of the last vehicle in the queue at regular intervals (e.g., every second).

Averaging: The average queue length is computed by summing the queue lengths recorded at each time step and dividing by the total number of time steps:

$$\text{Average Queue Length} = \frac{\sum(\text{Queue Length at each time step})}{\text{Number of time step}}$$

Tram-Specific Factors: For trams (60 meters long), the queue length reflects their fixed length and position relative to the stop line. The average is low (5.6 meters) because many signal cycles have no tram queue.

Numerical Example

We calculated the queue length for a **120-second signal cycle**. In this scenario, two trams pass through the intersection during this cycle. The traffic light turns green at **second 0** and stays green for **90 seconds**.

The **first tram** arrives at the **second 30**, during the green phase, so it doesn't stop.

The **second tram** arrives at the **second 100**, during the red phase, so it has to stop.

In VISSIM:

If **no tram** passes, the **queue length is 0**.

Between **seconds 0 and 99**, even though one tram passed, it didn't stop, so the **queue length stays 0**.

From the **second 100 to 120**, the second tram waits through the red light. For each second, the queue increases by 60 meters (the tram's length). Over 20 seconds, this becomes: **60 × 20 = 1200 meters** of total queue.

To find the **average queue length**, we divide the total queue length by the cycle time: **1200 / 120 = 10.0 meters**

In the simulation, VISSIM showed the **average queue length as 5.6 meters**. This means the tram was delayed at the intersection. To better understand this:

Multiply **5.6 meters × 3900 seconds** (the simulation duration) = **21,840 meters**.

Divide this by the **length of a tram (60 meters)** to see how many seconds trams were stopped:
21,840 / 60 = 364 seconds of total stopping time.

Divide this by the number of trams to see the average of trams stopped = **364 / 27= 13.5 seconds** for each tram

So, I used two indicators:

Queue length (in meters) to show how well the strategy reduced tram stops,

And the **delay** (in seconds) to show how much time the strategy saved.

Conclusions

The 5.6-meter tram queue length in the simulation reflects minimal average queuing, as many signal cycles have no trams stopped. VISSIM's queue length calculation, based on queue counters and time-averaged measurements, accurately captures this behavior.

PUBLICATIONS FROM THE THESIS

Conference Papers

1. Alhassan, H. M. A., & Akyıldız Alçura, G. (2025). Optimizing urban tram efficiency through transit signal priority: A case study in Istanbul. In İ. Erpay (Ed.), *7th BILSEL International World Science and Research Congress Book* (pp. 41–49). BILSEL Publishing. https://bilselkongreleri.com/wp-content/uploads/7.-BILSEL-DUNYA-BILIM-KONGRESI-KONGRE-KITABI.pdf