SAKARYA UNIVERSITY OF APPLIED SCIENCES
INSTITUTE OF GRADUATE EDUCATION

SYSTEMATIC EVALUATION OF PEDESTRIAN VOLUME ON UNSIGNALIZED INTERSECTION PERFORMANCE METRICS IN A SIMULATION ENVIRONMENT

M.Sc THESIS

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This thesis was accepted by the committee given below on 24/05/2023 by unanimously of votes in Institute of Graduate Education, Sakarya University of Applied Sciences.

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DECLARATION

All the data in the thesis are obtained by me within the framework of academic rules, all visual and written information and results are presented in accordance with academic and ethical rules, there is no manipulation in the data used, in case of benefiting from the works of others, it is referred to in accordance with scientific norms, I declare that it has not been used in any thesis work or any other university.

Nadher Mohammed Saeed NOMAN

24/05/2023

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ABBREVIATIONS

AASHTO	: American Association of State Highway and Transportation Officials
ADT	: Average Daily Traffic
ARRB	: Australian Road Research Board
CBD	: Central Business District
CO	: Carbon monoxide
CO_2	: Carbon Dioxide
FHA	: Federal Highway Administration
ft	: Foot
h	: Hour
HCM	: Highway Capacity Manual
km	: Kilometer
L	: Litre
LOS	: Level of Service
m	: Meter
min	: Minute
MSSI	: Municipality, Sapak, and Serdivan intersections
MUTCD	: Manual on Uniform Traffic Control Devices
NO	: Nitric oxide
NO_X	: Nitrogen oxides
N_2O	: Nitrogen dioxide
p	: person
ped	: pedestrian
PHF	: Peak-hour factor
PLOS	: Pedestrian level of service
PTV	: Planung Transport Verkehr AG

QL	: queue length
s	: Second
Scen	: Scenario
veh	: Vehicle
VI	: Vatan intersection
VOC	: Volatile organic compounds
W1	: Waiting area one
W2	: Waiting area tow

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ABSTRACT

The dilemma of traffic problems in urban areas has become a global concern over the last few decades. Growing populations and urbanization have contributed to increased demand for transportation, resulting in traffic congestion, high rates of air pollution, accidents, and other related issues affecting the environment and quality of life. Sustainable transportation has emerged as a viable solution to these challenges. Achieving sustainable transportation requires a multidisciplinary approach that considers transportation planning, policy, and technology. Strategies such as public transportation, active transportation modes, and intelligent transportation systems can contribute to the development of sustainable transportation systems. However, successful implementation of these strategies requires an understanding of local mobility patterns and behaviours as well as effective evaluation methods to assess their effectiveness. This study systematically evaluated the impact of pedestrian volume on performance metrics at unsignalized intersections. Four intersections were chosen in the Serdivan district within Sakarya city, in an area where commercial activity is expected to increase in the near term, which makes it a pedestrian attraction in addition to the current heavy traffic. The evaluation process was conducted in a simulated environment utilizing the VISSIM program by gradually increasing the pedestrian volume without changing the current vehicular traffic and monitoring the intersection performance metrics. Performance metrics such as delay, level of service, speed, number of stops, queuing, emissions, and fuel consumption for both vehicles and pedestrians were assessed. The results indicated that intersections that were already suffering from heavy vehicular traffic, specifically Sapak and Serdivan intersections, did not experience significant deterioration in vehicular performance metrics when pedestrian volume was increased. This can be attributed to the fact that the performance metrics were already failing in the current traffic conditions due to high vehicular traffic. On the other hand, the performance metrics of the vehicles at the Municipality and Vatan intersection that were witnessing low vehicular traffic and a fairly high volume of pedestrians appeared to be at acceptable levels. However, the deterioration began to appear noticeably after increasing the volumes of pedestrians by 200% at the Municipality intersection and 400% at the Vatan intersection (in the morning). The evaluation of pedestrian traffic was also critical in this study, whereby performance metrics for pedestrian traffic remained acceptable and were at good levels during all scenarios as long as the vehicles yielded to pedestrians approaching the crosswalks by giving them priority to cross, while the deterioration appeared in the case of the vehicles ignoring the pedestrians and not complying with giving them priority. The findings highlight the importance of evaluating intersection performance in relation to increasing pedestrian volume to promote sustainable mobility options and pedestrian-friendly urban environments.

Keywords: Sustainable Transportation, Performance Metrics, Simulation, VISSIM

SİNYALİZE OLMAYAN KAVŞAKLARDA YAYA TRAFİĞİ ARTIŞININ KAVŞAK PERFORMANS ÖLÇÜTLERİNE ETKİSİNİN SİMÜLASYON ORTAMINDA DEĞERLENDİRİLMESİ

ÖZET

Kentsel alanlardaki trafik sorunlarının ikilemi son birkaç on yılda küresel bir endişe haline gelmiştir. Artan nüfus ve kentleşme, taşımacılık talebindeki artışa katkıda bulunarak trafik sıkışıklığı, yüksek hava kirliliği oranları, kazalar ve diğer çevre ve yaşam kalitesini etkileyen sorunlara neden olmuştur. Sürdürülebilir ulaşım, bu zorluklara yönelik bir çözüm olarak ortaya çıkmıştır. Sürdürülebilir ulaşımın başarılması, ulaşım planlamasını, politikasını ve teknolojisini göz önünde bulunduran çok disiplinli bir yaklaşım gerektirir. Toplu taşıma, aktif ulaşım modları ve akıllı ulaşım sistemleri gibi stratejiler, sürdürülebilir ulaşım sistemlerinin geliştirilmesine katkı sağlayabilir. Ancak, bu stratejilerin başarılı bir şekilde uygulanması, etkin değerlendirme yöntemleriyle birlikte yerel hareketlilik modelleri ve davranışlarının anlaşılmasını gerektirir. Mevcut altyapının, mevcut trafik düzenlemelerinin ve beklenen yaya yoğunluğundaki artışların göz önünde bulundurularak değerlendirilmesi, sürdürülebilir ulaşım seçeneklerine geçiş çabalarını güçlendirmede kritik bir adımdır ve yaya dostu şehirler yaratmada önemlidir.

Etkili ulaşım planlaması, karar verme süreci için kritik olan doğru ve güvenilir trafik verilerini gerektirir. Ancak, veri toplama tek başına, olası senaryoların ve uygun karar mekanizmalarının değerlendirilmesi olmadan kentsel hareketlilik zorluklarını ele almada yetersiz kalır. Simülasyon teknikleri, ulaşım planlamasında kritik bir rol oynar, çünkü planlamacılara çeşitli senaryoları test etme ve ulaşım sistemindeki değişikliklerin etkisini öngörme imkanı sağlamaktadır. Simülasyon teknikleri ile planlamacılar farklı senaryoları modelleyebilir ve farklı politika ve müdahalelerin etkisini değerlendirebilir, böylece kentsel hareketliliği geliştirmek ve trafik sıkışıklığını azaltmak için en etkili çözümleri belirleme imkanı bulunmaktadır.

Bu çalışma kapsamında sinyalsiz kavşaklarda yaya hacminin performans ölçütlerine etkisi sistematik olarak değerlendirilmiştir. Serdivan bölgesinde, Sakarya şehrinde, alışveriş merkezlerine, okullara, kamu hizmeti binalarına ve yeni geliştirilen çekim merkezlerine yakınlığı nedeniyle yakın gelecekte ticari faaliyetin artması beklenen bir bölgede dört kavşak seçilmiştir. Bu, mevcut yoğun trafik durumuna ek olarak yaya trafiğini de çekici kılan bir alan yapmaktadır. Değerlendirme süreci, mevcut motorlu taşıtlı trafiği değiştirmeden yaya yoğunluğunu dereceli olarak artırarak VISSIM programı kullanılarak simüle edilen bir ortamda gerçekleştirilmiş ve kavşak performans ölçütleri izlenmiştir. Gecikme, hizmet seviyesi, hız, durma sayısı, kuyruk oluşumu, emisyon ve yakıt tüketimi gibi temel ölçütler ile gecikme, hizmet seviyesi, hız ve durma sayısı gibi yaya özel ölçütler, beş farklı senaryo boyunca yaya haciminin dereceli olarak arttığı sırasında değerlendirilen kritik parametrelerdir. Ayrıca, iki farklı araç-yaya çakışma modu simüle edilmiştir; ilk mod (tipik durum), teorik olarak beklendiği

gibi yayalara yol veren araçları temsil eder, ikinci mod (yerel durum) araçların çoğunlukla yaya haklarına saygı göstermediği, sahada gözlemlenen durumu temsil eder.

Çalışma, halihazırda yoğun motorlu taşıt trafiğine ve düşük yaya yoğunluğuna sahip Sapak ve Serdivan kavşaklarının, farklı senaryolar sırasında yaya yoğunluğunu artırdıklarında araç trafiğinin performans ölçütleri üzerinde önemli ve ani bir kötüleşme yaşamadığını ortaya koymuştur. Bu durum, performans ölçütlerinin zaten yüksek motorlu taşıt trafiğine bağlı olarak mevcut trafik koşullarında kötüleşmekte olduğu gerçeğine bağlanabilir. Yaya hacimlerindeki artımlı değişimin tutarlı ve hafif bir etkisi olmasına rağmen, araç trafiği için çoğu performans ölçümünde durumu önemli ölçüde kötüleştirmiştir. Bunun aksine, düşük motorlu taşıt trafiği ve oldukça yüksek yaya yoğunluğuna sahip olan Belediye ve Vatan kavşakları gibi kavşaklarda yaya yoğunluğundaki artış, motorlu taşıt trafiği performans ölçütlerinde ani bir kötüleşmeye neden olmuştur. Bu kavşaklarda motorlu taşıt trafik performans ölçütleri, mevcut trafik koşullarında nispeten iyiyken, yaya yoğunluğu yüzde 200 artırıldığında Belediye kavşağında ve Vatan kavşağında yüzde 400 artırıldığında (sabah saatlerinde) kötüleşme belirgin ve keskin bir şekilde ortaya çıkmaya başlamaktadır. Çalışmada yaya trafiği değerlendirmesi de önemliydi ve yaya trafiği için performans ölçütleri, araçların yaya geçitlerine yaklaşan yayanın tam önceliğini vererek, yaya haklarına saygı gösterdiği sürece tüm senaryolarda kabul edilebilir düzeyde ve iyi seviyelerde kalmıştır. Ancak, araçların yaya haklarına dikkat etmediği ve tam önceliği vermediği durumlarda kötüleşme ortaya çıkmaktadır.

Sonuç olarak, bu çalışma, yaya yoğunluğunun arttığı bağlamda kavşak performans ölçütlerinin değerlendirilmesinin, sürdürülebilir ve dirençli hareketlilik seçeneklerini teşvik etmek için önemini vurgulamaktadır, özellikle aktif ulaşım modlarına odaklanmaktadır. Çalışmanın bulguları, kentsel planlamacıları ve politika yapıcıları, yaya altyapısına yatırım yapma, aktif ulaşım modlarını teşvik etme ve trafik düzenlemelerini uygulama gerekliliği konusunda bilgilendirebilir. Bu şekilde kentsel alanları daha yaya dostu hale getirmeye yönelik çabalara katkıda bulunabilirler. Ayrıca, çalışma, yaya performans ölçütleri üzerine daha fazla araştırma ihtiyacını vurgulamaktadır. Bu sayede kentsel alanlarda yaya güvenliğini ve hareketliliği etkileyen faktörleri daha iyi anlamak mümkün olacaktır.

Anahtar Kelimeler: Sürdürülebilir Ulaşım, Performans Ölçütleri, Simülasyon, VISSIM

CHAPTER 1. INTRODUCTION

1.1 General Overview

What the world is witnessing now in terms of an industrial boom and an increase in urbanization in parallel with the increase in population density is reflected in negative effects on the environment in terms of emissions and pollutants, as well as the narrowing of urban living spaces. Therefore, many governments seek to reduce these impacts by relying on renewable energy and creating pedestrian-friendly environments known as pedestrian cities. Pedestrian cities are characterized by a way of life that enables individuals to carry out their daily activities without relying on vehicles, with essential amenities conveniently located within walking distance. Encouraging walking as the preferred mode of transport for short trips becomes pivotal in promoting sustainable transportation strategies and advancing the shift towards pedestrian cities.

In developing and underdeveloped countries like Turkey, there exists a disparity in the treatment of road users, with pedestrian traffic often not receiving the same priority as vehicular traffic, and often the primary goal is to increase the comfort of vehicles and their occupants, while pedestrian requirements may not always be explicitly taken into account. The integration of convenient walking routes, both in terms of safety and general enjoyment, reduces the number of tasks people use their vehicles for and encourages people to use walking as a means of reaching their destinations. This helps reduce fuel consumption, which in turn reduces air pollution and preserves the environment. In order to promote sustainable transportation and encourage pedestrians to walk instead of using motorized vehicles, safe and convenient pedestrian facilities are very important in this context. Pedestrian crossings at urban intersections are considered one of the most important pedestrian facilities, and the increase in walking activities at them has an impact on the performance metrics at the intersection. Accordingly, this study aims to evaluate the performance of intersections within Sakarya's commercial area in light of the anticipated growth in pedestrian activities in the future.

1.2 Research Objectives and Scope

This research is based on three main objectives:

- Evaluating the performance metrics of four selected unsignalized intersections during the incremental increase in pedestrian traffic, where there is an expected non-motorized mobility increase in the area,
- Identifying the critical point during the increase in pedestrian volumes, after which the performance metrics at the intersection breakdown further,
- Evaluating whether there is a difference between theoretical and observed behavior regarding giving priority to pedestrians at intersection crossings and its effect on intersection performance metrics.

The study focused on four unsignalized intersections in the Serdivan region of Sakarya city, an area experiencing recent growth in commercial activities that continues to expand, generating an increase in walking activities and micromobility transport. The scope of the study includes only these four intersections, but the conclusions may also be applicable in other locations with similar mobility patterns and in general. Data were collected for the morning and evening peak hours on three weekdays and one day on the weekend. The parameters were encoded and entered into the VISSIM simulation software, and the microscopic simulation process was carried out to study the effect of increasing walking activity on the performance metrics at the selected intersections. Pedestrian volume increments ranging from 200% to 1000% were intuitively chosen for the analysis without prior evaluation. The vehicular traffic remained constant based on collected field data, while the pedestrian volume incrementally increased. Two modes of vehicular-pedestrian conflict were also considered, once by assuming that vehicles comply with pedestrians by giving them priority to cross, representing the typical case, and the other by assuming that vehicles do not comply and pedestrians wait for the appropriate gap to cross, representing the local case.

1.3 Research Structure

The thesis consists of seven chapters.

Chapter 1 contains an overview of the study and its objectives.

Chapter 2 provides an introduction to transportation and traffic in urban areas and the problems it suffers from, in addition to the most important parameters, characteristics, and relationships related to vehicular and pedestrian traffic. The importance of walking as a sustainable mode of transportation and a step toward shifting to a strategy of pedestrian cities was also discussed.

Chapter 3 highlights intersections, their types, and traffic at intersections.

Chapter 4 focuses on performance measures at intersections related to vehicles and pedestrians, in addition to addressing previous studies related to evaluating performance at intersections using simulations.

Chapter 5 describes the methodology that was adopted, including the selection of the study area, data collection, modeling and analysis using VISSIM.

Chapter 6 presents the evaluation and discussion of the results of the analysis of the various scenarios.

Chapter 7 presents the conclusions and proposed recommendations.

CHAPTER 2. URBAN TRANSPORTATION AND TRAFFIC

2.1 Introduction

Urban traffic is one of the significant challenges facing cities and city environments, and as cities expand and urban development increases, cities face intense urban traffic problems. Some of these problems have emerged due to rapid urbanization, while others are the result of low-quality infrastructure, inconsistency in urban planning techniques, or poor traffic control management. As a consequence, we can draw the conclusion that urban traffic is regarded as a by-product of urbanization, which is frequently linked to the overarching causes of urban change, land use change, and urban redevelopment (Cheshmehzangi and Pourroostaei Ardakani, 2021).

For a long time, urban traffic issues have been a top concern in developed countries. While transportation systems in general and urban traffic in particular contribute significantly to those countries' economic well-being, they also have adverse impacts, so planners and decision-makers are developing and updating related programs as well as conducting studies and research to help solve these issues and their negative impacts.

2.2 Types of Urban Transportation Systems

Urban transportation and traffic have evolved over time, and various transportation systems have been adopted. In general, urban transportation is separated into public transportation and individual transportation. Buses, bus rapid transit, metro, tramway, and light rail systems are the most popular forms of urban public transport. Municipalities of cities seek to develop and encourage urban public transport due to its ease of access by all segments of society, its ability to be used more than once, enable certain and affordable fees for services, the presence of stops at frequent intervals, the availability of timetables for services and trip times, and other characteristics that characterize transportation systems as public transportation (Acar, 2004). The decisions taken regarding citizen transportation affect the quality of life in urban areas. City roads may be more reserved for citizens or occupied by vehicles, people's travel times may be excessively reduced or lengthened, and environmental pollution levels may remain below acceptable levels or rise to higher ones. The compatibility of transportation with life in cities expresses "sustainability" (Acar, 2004). Individual transportation is represented by automobiles, bicycles, and pedestrians. Automobiles include all vehicles that carry passengers other than buses. Within the wide vehicle category, passenger automobiles, motorbikes, sports and leisure vehicles are expressly included. Due to the high energy consumption and space occupied by vehicles in traffic as well as the need for more parking, modern transportation policies have adopted more sustainable modes of transportation as an alternative to vehicles, such as allocating a large space for active transportation (pedestrians and bicycles) in urban areas, allocating special lanes for bicycles and sidewalks for pedestrians, giving them priority at crossings and intersections, and designing facilities that encourage pedestrians to commute (AASHTO, 2018).

2.3 Urban Traffic Issues

2.3.1 Congestion

The main function of urban traffic is to improve efficiency by facilitating the movement of vehicles and people within the city. Urban traffic congestion is primarily caused by the increase in the number of vehicles and their utilization of the road system. More specifically, it stems from the concentration of travel flows at peak hours. Depending on the mix of traffic, different parts of the city may experience congestion at different times of the day, but most major cities experience serious congestion in the center areas during peak hours. As a result, the importance of pedestrians in cities, especially in developing countries, is constantly increasing because the entry of vehicles is becoming more prevalent in cities, and as a result, the presence of pedestrians in urban spaces will be less.

Traffic congestion is defined as the increase in the number of vehicles on a section of roadway at a particular time, resulting in speeds that are slower and sometimes becoming stop-and-go traffic. Among the most important causes of congestion are traffic demand, intermittent disruption of traffic flow at crossings and road capacity, as well as traffic-influencing events such as accidents, work zones, and weather (FHWA and Cambridge Systematics, 2005).

2.3.2 Difficulty of pedestrian mobility

As a result of the huge population increase and the resulting increase use of motorized vehicles, the absence of policies which ensure the protection and safety of pedestrians and cyclists, deficiencies in the construction of bridges and tunnels, and strategies that encourage the utilize of public transport in congested areas, which represented a common element of the sources of environmental problems in the city, this prompted the municipalities of cities and those interested in urban planning to adopt strategies and laws to ensure the increase of pedestrian mobility within cities, freedom of movement for people, and provide a means of safety for their lives, especially the minor age groups and the elderly.

2.3.3 Traffic accidents

One of the problems of urban traffic is traffic accidents, which are often the result of traffic congestion as well as drivers' failure to adopt, exceed, or neglect traffic rules in order to achieve their own behavior, which is reflected in the lives of individuals and properties. Traffic engineers bear a great responsibility to ensure the safety and security of road users by providing safe traffic movements. Traffic accidents can't be fully prevented, however, through proper traffic engineering applications and management, the accident rate will be reduced to an explicit scope. For this reason, it is necessary to conduct a systematic investigation of road accidents.

Road accidents claim the lives of approximately 1.24 million people each year, and according to the first global report on the condition of road safety, 46% of those fatalities involve pedestrians, cyclists, or two-wheeled motorcyclists. The Second Global Report on the Status of Road Safety also reviewed the situation of pedestrians separately from other road users at risk and indicated that 22% of those who died on the world's roads were pedestrians. As shown in both reports and the World Report on Road

Traffic Injury Prevention, there are regional and national differences in the distribution of road-user mortality (Krug et al., 2014).

2.3.4 Environmental impacts

he problem of pollution is a dilemma facing most cities in the world, which is mostly brought on by the emissions of gases, exhausts, and other pollutants from vehicles and other forms of transportation, and this leads to a wide variety of health and environmental issues. According to studies conducted in urban areas in Europe, 70% of the pollutants emitted from transport are generated there, in addition to 40% of CO2 due to road transport (Pomykala, 2018). Other environmental impacts from traffic include noise, visual pollution, destruction of natural habitats, and isolation of communities by transportation routes. From this perspective, proper and effective network infrastructure planning is essential to ensuring safety, inclusion, and convenience for users. To ensure the spread of soft mobility, as is the case for road infrastructure dedicated to vehicles, bicycle and pedestrian paths must also be included in program projects and some specific characteristics respected (Santilli et al., 2021).

2.3.5 Parking difficulty

Parking is one of the most significant issues brought about by the increase in traffic on the roads. It's a consequence of the gradual development of transportation. The availability of less space in urban areas has increased the demand for parking spaces, especially in areas like the Central Business District (CBD). Urbanely, it is impossible for a large city to provide a parking space for all who wish to enter the city center without applying restrictions. This might lead to illegal parking, which would obstruct traffic flow.

2.4 Vehicle Traffic

The study of urban traffic behavior and the design of facilities to ensure that traffic flows smoothly, safely, and efficiently are the focus of urban traffic. A complete understanding of traffic flow parameters, including their interrelationships, is necessary to comprehend traffic behavior. The fundamental concepts of traffic flow will be covered in this section. The traffic stream includes a combination of driver and vehicle behavior. The driver's or human behavior being non-uniform, the traffic stream is also non-uniform in nature. It is influenced not only by the individual characteristics of both the vehicle and the human but also by how such units interact with one another. As a result, the flow of traffic through a street with specific characteristics will vary depending on the location and time corresponding to changes in human behavior (Mathew, 2006).

Traffic flow is divided into two basic types: intermittent and uninterrupted. Uninterrupted flow can be expressed as the flow that occurs when vehicles traversing a length of roadway do not have to stop for any external reason, such as traffic controllers. The flow of vehicles on highways or at other limited-access facilities where there are no traffic lights or signs to interrupt traffic is an uninterrupted flow. Interrupted flow occurs when flow is periodically interrupted by external means, primarily traffic control devices such as stop and yield signs and traffic signals. The flow of vehicles on arterial roads within the city promises intermittent flow (Myer Kutz, 2004).

2.4.1 Vehicle flow parameters

In order to evaluate and analyze vehicle traffic on the roadways, three important traffic flow parameters are used: traffic volume or flow rate, traffic speed, and traffic density.

2.4.1.1 Volume and flow rate

The total number of vehicles passing across a certain point or section of a lane or roadway during a given time interval is referred to as volume. Volumes are typically expressed in terms of annual, daily, hourly, or sub-hourly periods. A flow rate is the equivalent hourly rate at which vehicles pass over a given point during a given time interval of less than 1 hour, usually 15 minutes (HCM, 2000).

Peak flow rates and hourly volumes produce the peak-hour factor (PHF), the ratio of total hourly volume to the peak flow rate within the hour, computed by Equation 2.1.

$$PHF = \frac{Hourly\ volume}{Peak\ flow\ rate\ (within\ the\ hour)} \tag{2.1}$$

If 15-minute periods are utilized, the PHF is possible to obtained by Equation 2.2.

$$PHF\ =\ \frac{V}{4 \text{ x } V_{15}} \tag{2.2}$$

Where,

PHF = peak hour factor,

V = peak hour volume (veh/h), and

V_{15} = volume for peak 15-min period (veh).

The PHF describes trip-generation characteristics. When PHF is identified, it is possible to utilize it to convert a peak-hour volume to an estimated peak rate of flow within an hour, as shown in Equation 2.3.

$$v = \frac{V}{PHF} \tag{2.3}$$

Where v is the flow rate for a peak 15-minute period, expressed in vehicles per hour, and the other variables are as stated previously.

Lower PHF values indicate greater flow variability within the hour, while higher values indicate less flow variability. When using hourly counts, the PHF can range from 1.00, which indicates that the same demand occurs throughout each 15-minute period of the hour, to 0.25, which indicates that the whole hourly demand occurs during the peak 15 minutes (HCM, 2000).

2.4.1.2 Flow at intersections

The analysis of traffic flow at intersections is a more intricate task owing to the inherent time dimension that is involved in allocating space for the conflicting traffic flows. The control of interrupted flow at intersections is generally achieved by means of traffic lights, stop signs, or giving way. Saturation flow is a crucial operational measure of road traffic, particularly at signalized intersections. The assessment of saturation flow at an intersection encompasses several factors, including the geometric design of the intersection, the degree of conflict between the opposing vehicles or pedestrian flows at crosswalks, and the rate of turning left and right (Bang et al., 2016). The saturation flow rate represents the number of vehicles per lane per hour passing through the intersection if the green light is available for a full hour without stopping. The speed of vehicles and gaps, as well as other factors including the number and width of lanes, conflicting vehicles, and pedestrian activities, are all strongly related to the saturation flow rate of the road network. According to HCM, the saturation flow rate per lane typically ranges between 1,500 and 2,000 veh/h and can be calculated using Equation 2.4 (HCM, 2010a). The resulting value from the previous equation is considered the basic saturation flow rate and is adjusted for a set of conditions such as lane width and usage, vehicle type, bus and pedestrian bicycle blockage, left or right turns, type of area, grad and parking.

$$s = \frac{3600}{h} \tag{2.4}$$

Where,

s = saturation flow rate (veh/h), and,

h = saturation headway (s).

The degree of saturation for circular intersections represents the ratio between the demand capacity and the entry capacity. When the degree of saturation exceeds a certain limit, the work of the intersection deteriorates, the delay increases, and queues begin to form. Therefore, according to HCM, if the degree of saturation is greater than 0.9, the average control delay is significantly affected by the length of the analysis period and queues begin to form, while the Australian road design sets this value at 0.85 (Robinson et al., 2000).

2.4.1.3 Speed

Speed is a measure of the quality of travel as drivers and passengers are more concerned with travel speed than with aspects of traffic design. The vehicle speed is expressed as the distance it travels per unit of time and usually expressed in kilometers per hour (km/h). Average travel speed is used as the speed measure because it is easily computed from observation of individual vehicles within the traffic stream and is the most statistically relevant measure in relationships with other variables (HCM, 2000). The average travel speed can be expressed in two ways. The first is the arithmetic mean of the vehicle speeds observed at some designated point along the roadway. This is referred to as the time-mean speed and is expressed by the Equation 2.5 (HCM, 2000; Mannering and Washburn, 2013).

$$\bar{u}_t = \frac{\sum_{i=1}^{n} u_i}{n} \tag{2.5}$$

Where,

$\bar{u}_t$ = time-mean speed in unit distance per unit time,

u_i = spot speed (the speed of the vehicle at the designated point on the highway, as might be obtained using a radar gun) of the *i*th vehicle, and

n = number of measured vehicle spot speeds.

The second definition of speed, which is more applicable in the context of traffic studies, is determined on the basis of the time necessary for a vehicle to travel a specified distance on the roadway. This measure of average traffic speed is referred to as the space-mean speed and is expressed as in the Equation 2.6. In this equation, it is assumed that the travel time for all vehicles is measured over the same length of roadway, as outlined in previous (HCM, 2000; Mannering and Washburn, 2013).

$$\bar{u}_s = \frac{l}{\bar{t}} \tag{2.6}$$

Where,

$\bar{u}_s$ = space-mean speed in unit distance per unit time,

l = length of roadway used for travel time measurement of vehicles, and

$\bar{t}$ = average vehicle travel time, defined as in the Equation 2.7.

$$\bar{t} = \frac{1}{n}\sum_{i=1}^{n} t_i \qquad (2.7)$$

Where,

t_i = time necessary for vehicle i to travel a roadway section of length l, and

n = number of measured vehicle travel times.

2.4.1.4 Density

The number of vehicles occupying a specific length of a lane or roadway at a particular instant is known as density, and it is commonly expressed as vehicles per kilometer (km) or passenger cars per kilometer. High densities indicate that individual vehicles are relatively close to each other, whereas low densities indicate greater distances between vehicles. Density can be estimated using relationships between density, flow, and speed, as illustrated by Equation 2.8 below (Mannering and Washburn, 2013).

$$k = \frac{n}{l} \qquad (2.8)$$

Where,

k = traffic density in vehicles per unit distance,

n = number of vehicles occupying some length of roadway at some specified time, and
l = length of roadway.

The density can also be related to the individual spacing between successive vehicles (measured from front bumper to front bumper). The roadway length (l) in Equation 2.9 can be defined as:

$$l = \sum_{i=1}^{n} s_i \qquad (2.9)$$

Where,

s_i = spacing of the ith vehicle (the distance between vehicles i and i-1, measured between the front bumpers), and

n = number of measured vehicle spacing.

2.4.1.5 Headway and gap

Headway and gap are microscopic measures to describe the distance between individual vehicles. Headway can be defined as the time it takes for the leading vehicle and the trailing vehicle to arrive when they pass specific points on the road. it is measured from the same point on each vehicle and is indicated in Equation 2.10 (Myer Kutz, 2004).

$$h_a = \frac{1}{v} \tag{2.10}$$

Where,

h_a = average headway, and

v = rate of flow.

A gap refers to the duration separating the departure of the first vehicle and the arrival of the following one at a certain point on the road. Headway focuses on elapsed time from front to front, while the gap from back to front. Figure 2.1 shows the difference between the gap and headway.

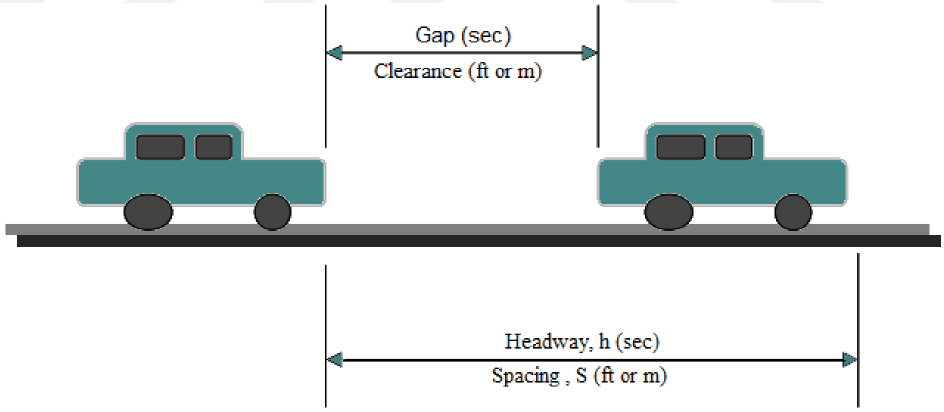

Figure 2.1 : Illustration of gap and headway definition.

2.4.2 Relationships among basic parameters

The flow-speed-density equation (Equation 2.11) is a beneficial technique for evaluating the operation of transportation infrastructure. The equation describes the relationship between speed, density, and flow under continuous flow conditions, such as on a motorway or in an urban transport network (Myer Kutz, 2004).

$$q = u * k \tag{2.11}$$

Where,

q = flow (veh/h),

u = space mean (average running) speed (km/h), and

k = density (veh/km, veh/h).

All of the flow, speed, and density relationships and their interactions are graphically represented in Figure 2.2, also known as the traffic flow basic diagrams.

The relationship between speed and density is constantly decreasing. The speed decreases as the intensity increases. This diagram shows where the flow is zero in two cases: either there are no vehicles on the road, which means the density is zero and the speed corresponds to free flow speed u_f, or the vehicles come to a complete stop due to traffic congestion, in which case their speed is zero and the density assumes jam density, k_j. The peak values of the speed-flow curve and the density-flow curve occur at maximum flow, which means the full capacity of the facility. The critical speed u_{cap} and critical density k_{cap} indicate the corresponding speed and density at which the maximum amplitude occurs (Mannering and Washburn, 2013; Myer Kutz, 2004).

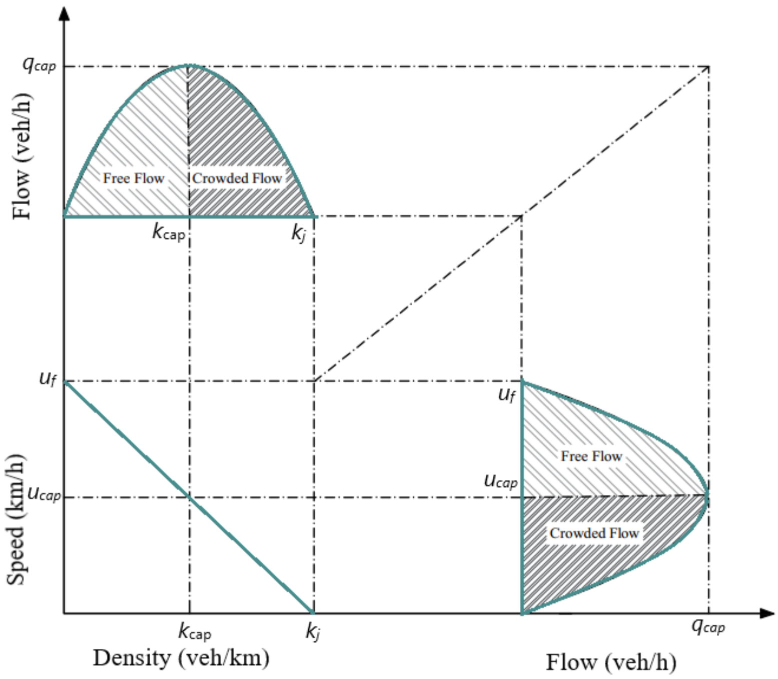

Figure 2.2 : Flow-density, speed-density, and speed-flow relationships.

2.5 Pedestrian Traffic

2.5.1 Pedestrian and walkability

In transportation terminology, a pedestrian encompasses individuals who initiate and conclude their journeys on foot, including various categories such as pedestrians with mobility aids (wheelchair users) and those utilizing small wheeled devices (children) (NZTA, 2009). The United States Department of Transportation defines pedestrians as anyone who uses a sidewalk, including those who travel with the help of wheelchairs. Creating a pedestrian-friendly environment necessitates meticulous attention to every detail, ensuring that all facilities are accessible to pedestrians of diverse abilities. The objective is to go beyond the mere installation of sidewalks or signage and instead prioritize comprehensive accessibility for all pedestrians, including those with disabilities (Zegeer et al., 2001).

Over time, the definition of a pedestrian has undergone transformation due to advancements in transportation and the emergence of vehicular dominance on roadways, particularly within urban settings. Previously, anyone walking on the road was generally classified as a pedestrian. However, as vehicles proliferated and gained control over road networks, the definition evolved to encompass individuals utilizing dedicated spaces such as sidewalks and other designated paths for pedestrian use. These paths can be described as designated surfaces exclusively intended for the movement of pedestrians, characterized by their segregation from traffic and vehicular presence (Şenkaynak, 2010).

Promoting walkability stands as a pivotal endeavor in fostering sustainable transportation within urban environments. Recent urban planning studies have delved into the exploration of walkability, yielding a variety of interpretations within the scholarly discourse. The term "walkability" carries different interpretations in research and discussions. Some interpretations consider walkability by focusing on environmental factors that contribute to the creation of walkable environments, such as facilitating crossing, increasing safety and making them attractive, whereas others focus on the results of walking that are reinforced by the presence of such environments, such as sustainable transportation, reducing environmental impact and improving health.

Certain interpretations adopt a comprehensive standpoint, perceiving walkability as a holistic concept that offers both a design solution and a remedy for urban challenges (Forsyth, 2015). Walkability relates to the possibility or ease of access to destinations, which represents one of the issues in urban areas (S.L. and K.J, 2001).

2.5.2 Neglect of walking in planning and policies

Walking, despite being the most prominent mode of transportation, has often been overlooked and marginalized in transportation planning and is viewed as a secondary mode of travel, particularly in developing nations. The construction of transportation systems in the more recent half of the 20th century was mainly geared towards the vehicle network by improving traffic conditions for vehicles through traffic management, reducing travel times and delays, and taking care of travel lanes and parking lots, with few or no pedestrian facilities. This encouraged more road users to use the vehicles, regardless of the long-term negative environmental impact (Matthews, 2022).

Data on pedestrians is rarely captured in government statistics on mobility and is neglected while great emphasis is placed on data on motorized traffic. Pedestrian-related data such as travel times, trip length, delays, accidents, destination density, and service level are all performance measures that help improve walkability and pedestrian infrastructure. On the other side, the elimination of pedestrians from the planning of urban and suburban settlements led to the promotion of car ownership, which resulted in the popularity of vehicle use at the expense of pedestrians. As a consequence, residences and destinations became separated from each other by large distances (International Transport Forum, 2012).

2.5.3 Walking strategy importance and goals

Walking represents the most prevalent, efficient, and cost-effective mode of transportation, as well as being environmentally friendly. Most trips made by other transport modes include walking, which is often the first and last mode of transport used, with most trips starting and finishing on foot, regardless of the primary mode of travel (NZTA, 2009). In other words, walking is how users of other transport modes reach their final destinations. It is not only a mode of transport, it is also a mode of pleasure. People walk for enjoyment on all kinds of infrastructure. Prioritizing walking in urban transportation plans not only reduces reliance on vehicles but also helps achieve environmental goals and promotes a healthier lifestyle. Reliance on walking also has significant potential to support high-level government agendas for more sustainable development (Elissa Goughnour et al., 2020; International Transport Forum, 2012).

Embracing walking as a convenient and secure mode of transportation significantly enhances road users' safety. By promoting walking and encouraging greater usage of public transportation instead of vehicles, congestion is reduced, diminishing the likelihood of conflicts between pedestrians and other road users, particularly at intersections and crossings. Such an approach fosters a safe and livable environment where the risk of accidents and potential hazards is minimized. Emphasizing walking as a transportation strategy not only facilitates efficient mobility but also cultivates harmonious coexistence among all road users (International Transport Forum, 2012). By embracing walking and encouraging increased usage of public transportation over vehicles, cities can advance towards more sustainable development.

2.5.4 Cities for pedestrian

Recently, concern for the environment began to take a greater turn, and transportation policies paid great attention to encouraging walking and the use of public transportation (Hassan, 2013). Creating attractive areas for pedestrian comfort and enjoyment is a critical component of new urbanism. Among the most coveted urban environments worldwide are cities characterized by comprehensive networks of car-free streets, often referred to as pedestrian cities. Transitioning towards pedestrian cities has emerged as a strategic objective pursued by numerous countries in recent years. Pedestrian cities offer a healthy and serene atmosphere devoid of noise and pollutants, as well as public spaces that are comfortable, attractive, and safe. The integration of comfortable walking routes, in terms of both safety and general pleasure, reduces the number of tasks people use their vehicles for and encourages people to use walking as a way to reach their destinations. This contributes to a reduction in fuel consumption, which in turn reduces air pollution and protects the environment (International Transport Forum, 2012).

The researchers discovered a strong correlation between physical activity and the urban environmental network. According to Sallis et al. (2016), in 14 diverse cities, there was a direct correlation between walking rates and various elements of the physical environment, such as residential density, intersection density, public transport availability, and the presence of parks. This correlation underscores the importance of the urban landscape in promoting physical activity. As this relationship gains recognition, it is increasingly highlighted in popular media, emphasizing the significance of pedestrian activity rates and the role of the urban environment in shaping public health outcomes.

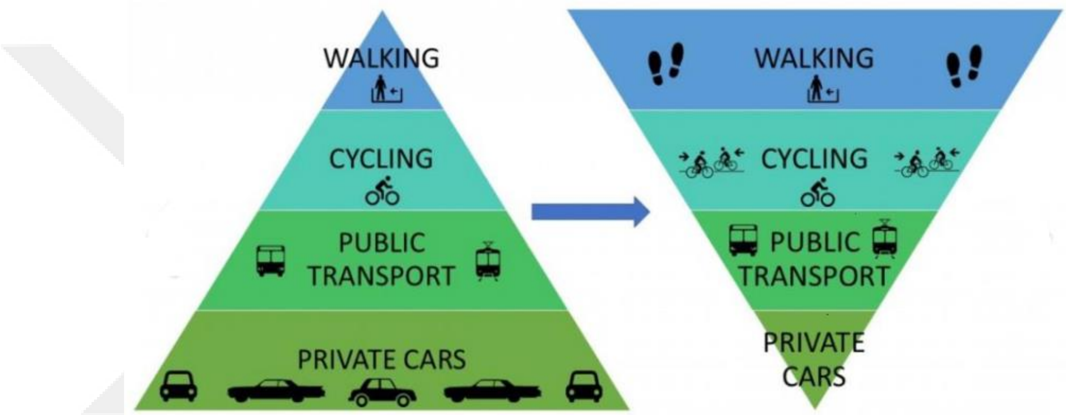

Figure 2.3 : Illustration of transformation strategy to pedestrian cities.

Walkable urban environments combined with public transportation services are better economically since they are considered an attractive environment for visitors and investment (International Transport Forum, 2012). According to a study conducted by George Washington College and the Urban Land Institute, the demand for office space is higher in urban areas where pedestrians are active than in vehicular-oriented areas (Loh et al., 2019). Figure 2.3 shows an illustration of the transformation strategy for pedestrian cities.

2.5.5 Pedestrian characteristics

2.5.5.1 Pedestrian space requirements

To achieve the standards of minimum pedestrian space according to HCM, an ellipse shape of 1.5 ft by 2 ft, resulting from the depth of the body and the width of the shoulders, has been adopted, and this serves as the realistic minimum for standing pedestrians (HCM, 2010a).

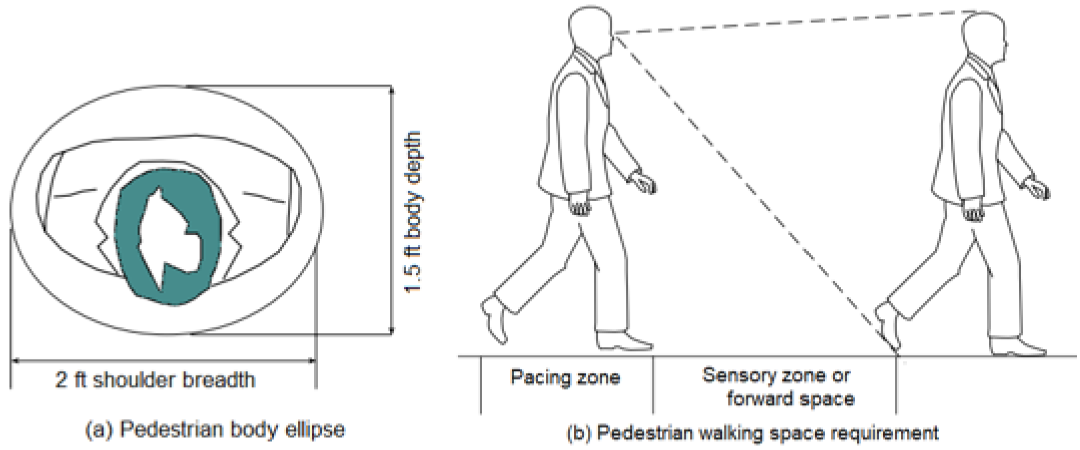

Figure 2.4 : Pedestrian space requirements (HCM2010).

In terms of pedestrian movement, the concept of forward space plays a crucial role as pedestrians strive to navigate their surroundings without colliding with others. The interpretation of forward space varies across cultures and countries, and its significance lies in its impact on both the volume of pedestrians that can pass through a specific location within a given timeframe and the pace at which individuals can travel. Figure 2.4 (a) depicts the minimum practical space required for stationary pedestrians, while Figure 2.4 (b) illustrates the forward space, which is further divided into a pacing zone and a sensory zone (HCM, 2010a).

2.5.5.2 Walking speed

Pedestrian speed is a major factor in the design and development of pedestrian facilities. The desired speed varies with several factors, including age, gender, purpose of the trip, group size, crossing location, and weather. To determine this desired speed, the density of pedestrians should be low enough so that no other pedestrians influence it (Hassan, 2013).

Pedestrian speed is influenced by various factors, including age. Research indicates that the average walking speed differs significantly between pedestrians aged 13 to 65 years and older pedestrians, with respective speeds of 4.74 ft/s and 4.25 ft/s. When determining crossing times for pedestrians, the 15th percentile crossing speed is considered. If the proportion of elderly pedestrians is below 20% of the total pedestrian population, a crossing speed of 3.5 ft/s is used. However, if the proportion of elderly pedestrians exceeds 20%, the crossing speed is adjusted to 3 ft/s. It is important to note that other factors, such as the presence of children, can further contribute to reduced crossing speeds (HCM, 2010a). In a study of 11 intersections that analyzed data from 1947 pedestrian crossing events, Gates et al. (2006) noticed that pedestrian speed is affected by age, disability, traffic control status, and group size. Pedestrians over the age of 65 were the slowest of all age groups, with a mean and 15th percentile walking speeds of 3.81 ft/s and 3.02 ft/s, respectively. Children and people with physical disabilities also demonstrated crossing speeds comparable to those of individuals over the age of 65. Individual pedestrians were also faster than pedestrians in groups by 0.4–0.6 ft/s on average. Pedestrian gender showed little effect on pedestrian crossing speed, as men walked on average 0.1 to 0.2 ft/s faster than women of the same age group, and young men were the fastest pedestrians, while older women were the slowest. On the other hand, the traffic control conditions had a noticeable effect as pedestrians under the WALK signal walked at a slower speed than those who walked under the DON'T WALK and FLASHING DON'T WALK signals, on average approximately 0.5–0.6 ft/s. Knoblauch et al. (1996), in their field study on pedestrian speed, highlighted the influence of weather conditions and noticed that there was a noticeable effect of the weather on the speed of pedestrians, especially adults, as they walked slowly when it snowed, and one of the slowest 15th percentile values observed was 2.94 ft/s when they crossed snowy roads. Laplante et al. (2004) reviewed the versions of the Manual on Uniform Traffic Control Devices (MUTCD) between 1948 and 2004 and concluded that it was recommended to use 3 ft/s as the minimum speed to cross the walking interval in addition to the clearance interval. Ünal and Saplıoğlu (2020) conducted a study in Mersin, Turkey, to examine the effects of gender, age, group behavior, load condition in hand, phone busyness, traffic, and pedestrian volume on crossing speed. The study concluded that the average crossing speed was 1.14 m/s. In another study by SAPLIOĞLU and FAISAL (2020), which was conducted at the signalized pedestrian crossings in Isparta city, the average speed of pedestrians was 88 m/s. Another study conducted in Istanbul aimed to determine pedestrian speeds and factors influencing them at pedestrian crossings, and according to the data obtained, the average pedestrian speed was determined to be 1.25 m/s (Kuşakcı et al., 2008).

2.5.5.3 Pedestrian start-up time

At signalized intersections, pedestrians may experience delays due to factors such as the time required for perception and interaction or to ensure that there are no vehicles at or close to the pedestrian crossing area (HCM, 2010a). This reaction time plays a significant role in determining the overall time required for pedestrians to safely and efficiently navigate signalized crossings.

In a study conducted by Ma et al. (2013), focusing on pedestrian perception and reaction time, it was found that pedestrians aged 51 years and older have an average perception and reaction time of 0.51 seconds, whereas pedestrians under 50 years old exhibit an average time of 0.23 seconds. Peters et al. (2015) examined the average perception and reaction time of pedestrians waiting on the sidewalk versus those waiting on the curb, revealing respective values of 0.51 seconds and 0.23 seconds. Knoblauch et al. (1996) investigated the start-up time for pedestrians over 65 years old and observed a duration of 2.5 seconds for individual pedestrians and 2.43 seconds for pedestrians in groups. Younger pedestrians, both individual and grouped, displayed an average start-up time of 1.93 seconds. The Highway Capacity Manual provides an estimate of the average start-up time for pedestrians at 3 seconds (HCM, 2010a).

2.5.5.4 Pedestrian compliance behavior

Crossing compliance for pedestrians is defined as the percentage of pedestrians who cross the road with the WALK signal indication and within the area designated for crossing, but a large proportion of pedestrians cross without complying with the pedestrian signal or the area designated for crossing, and this percentage increases with the increase in the pedestrian delay at the signal as pedestrians begin to engage in risk-taking behavior when they experience a delay of more than 30 seconds, which is the maximum wait time for pedestrians recommended by the Highway Capacity Manual (HCM, 2000; Sisiopiku and Akin, 2003).

2.5.6 Pedestrian flow parameters

Understanding pedestrian flow is essential to designing all pedestrian facilities for safety, convenience, and quick access to destinations. The specific measures of pedestrian flow are somewhat similar to those used for the flow of vehicles, such as freedom of choice, overtaking, and the desired speed, with a difference in some other measures related specifically to pedestrian flow, such as maneuverability without conflicts or changes in speed, the ability to cross the stream of pedestrian flow, walking against the main direction of the flow, and the delay at signals (HCM, 2000). A comprehensive study of pedestrian flow characteristics (such as flow, speed, density, space, free flow speed and jam density) and their relationships is important to obtain a clear visualization. towards urban traffic planning (Banerjee et al., 2018).

2.5.6.1 Relationships among basic parameters

The basic relationship that relates pedestrian flow to density and speed is illustrated by Equation 2.12 and is analogous to that of vehicular flow (HCM, 2010a).

$$V_{ped} = S_{ped} * D_{ped} \quad (2.12)$$

Where,

v_{ped} = unit flow rate (p/min/ft),

S_{ped} = pedestrian speed (ft/min), and

D_{ped} = pedestrian density (p/ft2).

The flow in the previous equation represents the flow of a predefined unit width and is used as a more mutually useful alternative expression for density or space, as in Equation 2.13.

$$v_{ped} = \frac{S_{ped}}{M} \quad (2.13)$$

Where, M is the pedestrian space (ft2/p).

The previously described relationship between flow, speed, and density explains in detail the characteristics of pedestrian flow under different conditions of congestion.

Utilizing simplified diagrams depicting this relationship facilitates a comprehensive comprehension of capacity and level of service values, enables the evaluation of pedestrian flow models (microscopic and macroscopic), and assists in the design of dynamic simulation models (Banerjee et al., 2018). Numerous studies conducted by researchers have highlighted notable disparities in basic diagrams based on pedestrian flow characteristics. In a study conducted by Zhang and Seyfried (2013), it was concluded that there exist variations in pedestrian flow characteristics between unidirectional and bidirectional flows, with the maximum value of unidirectional flow reaching 2 $(m\cdot s)^{-1}$ while bidirectional flow peaked at 1.5 $(m\cdot s)^{-1}$. Daamen et al. (2005), conducted a comprehensive review of experimental results from various researchers, analyzing basic diagrams of pedestrian flow characteristics in different infrastructures and flow compositions. The results demonstrated significant variations in jam density and capacity across different scenarios. These findings contribute to a deep understanding of pedestrian flow behavior and provide valuable insights for the design.

Speed-density relationships

Pedestrian flow measures such as speed, density, and volume in restricted-width facilities that have no cross-flows have a relationship similar to that of vehicular flow. Where it is apparent that the degree of mobility and walking speed given to individual walkers decreases as pedestrian volume and density increase and the area where they can move decreases. Figure 2.5 depicts the relationship between pedestrian speed and density for three different pedestrian categories (HCM, 2010a).

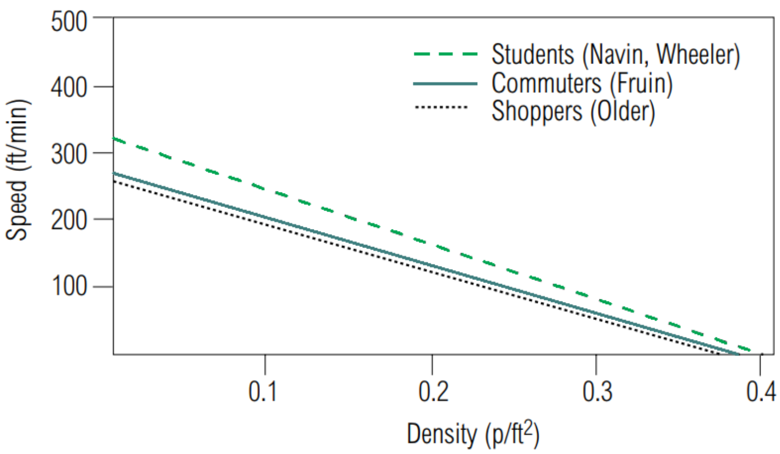

Figure 2.5 : Speed-density relationships (HCM2010).

Flow-density relationships

The capacity of a walkway facility represents the maximum flow that the facility can accommodate. Figure 2.6 illustrates the fundamental relationship between flow and space, highlighting that the maximum unit flow is achieved within a narrow range of densities, typically with an average space of 5 to 9 ft^2/p. Consequently, for flows nearing capacity, it is essential to allocate an average of 5 to 9 ft^2 of space per moving pedestrian. However, it is important to note that at this level of flow and within this restricted space, pedestrian speed and maneuverability become constrained. As the available space diminishes, there is a significant decrease in the flow rate, ultimately leading to a complete halt of movement when the allocated space reaches a minimum of 2 to 4 ft^2/p (HCM, 2010a).

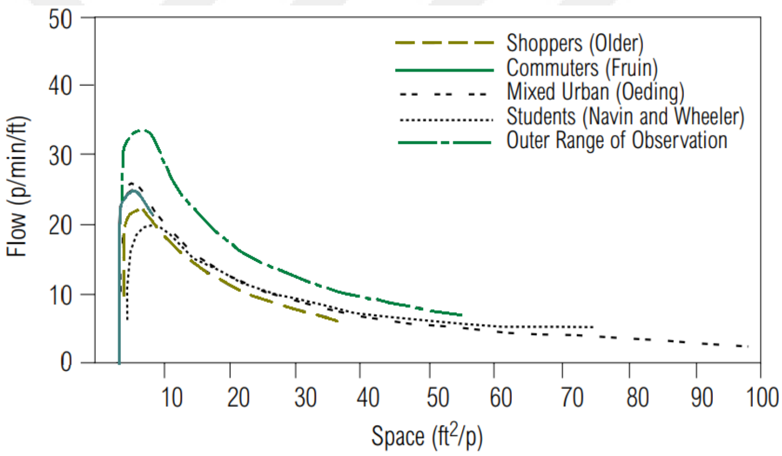

Figure 2.6 : Flow-density relationships (HCM2010).

Speed-flow relationships

The relationship of pedestrian flow to speed appears analogous to that of vehicles: as the flow increases, there is a decrease in speed due to close interactions between pedestrians until the congestion reaches a critical point and becomes difficult to move, at which point the flow and speed decrease at the same time. On the other hand, if the flow is low, the pedestrian can move and maneuver freely to walk at a higher speed. Figure 2.7 illustrates the relationship between pedestrian flow and speed (HCM, 2010a).

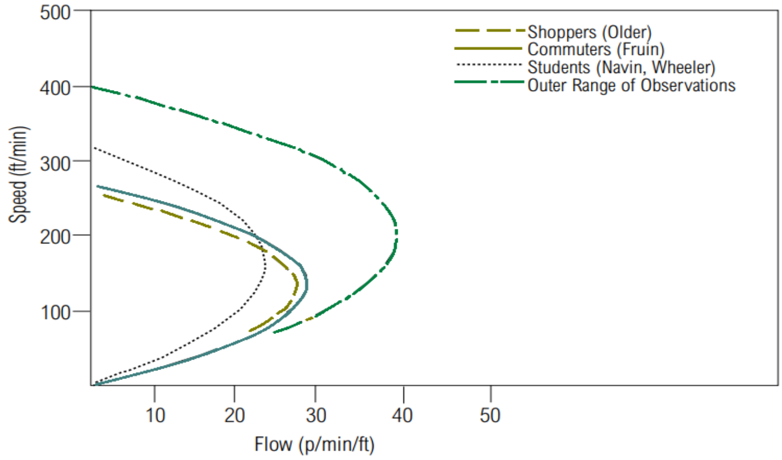

Figure 2.7 : Speed-flow relationships (HCM2010).

Speed-Space Relationships

The speed of pedestrians increases with more open space available to cross until they feel comfortable. However, if the free space available to pedestrians continues to increase, the walking speed will continue to be stable at the rate at which pedestrians feel comfortable. This relationship between pedestrian speed and available space is illustrated in Figure 2.8, as the lowest average area at which the slowest pedestrian can reach the required speed is 15 ft2/p, while pedestrians who walk at 350 ft/min need an average area of 40 ft2/p to achieve their speed (HCM, 2010a).

All the relationships that were mentioned previously still apply in the case of linear flow in restricted corridors such as bridges and underground passages, but they become more complex when applied to urban sidewalks and walkways due to cross-flows, immobile pedestrians, and the possibility of extending pedestrians outside the walkway. These cross-flows disrupt speed-flow relationships, reducing pedestrian speeds at equivalent flow rates. In addition, the maneuvers that pedestrians do around immobile pedestrians reduce the available width of the walkway, and this makes the flow low. Pedestrians on open walkways tend to walk outside these walkways in cases of high density, and this leads to disruption of these facilities before they reach their maximum flow. Understanding these complexities is crucial for designing efficient and effective pedestrian facilities in urban environments (HCM, 2010a).

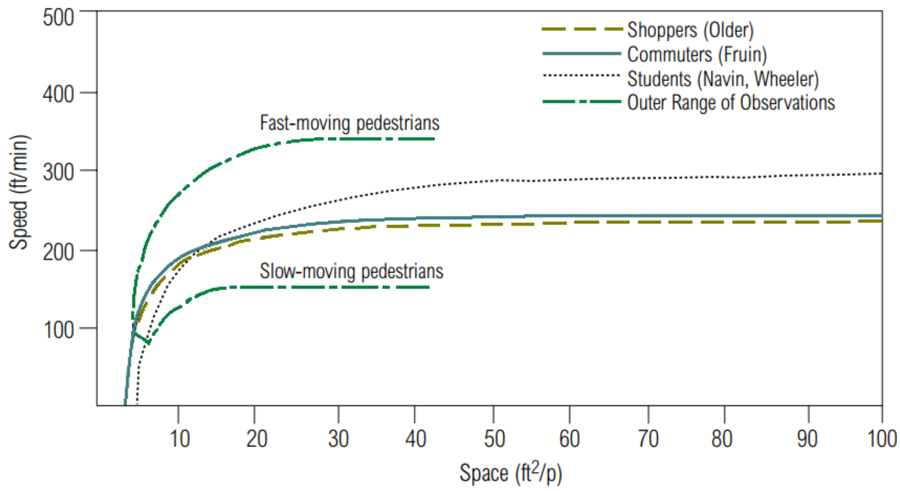

Figure 2.8 : Speed-space relationships (HCM2010).

2.5.7 Pedestrian flow measurements

Accurate calculation of pedestrian flows plays a pivotal role in the design of pedestrian facilities and ensuring their security and safety, in addition to assisting in determining the level of service and understanding the causes of delays. On-site measurements using pen and paper or hand-held clicker counters are one of the earliest techniques for calculating pedestrian flows. Despite the advancements in technology, these manual measurement methods are still utilized in practice. In recent years, video recording has been incorporated as a supplementary approach, allowing for more precise and reliable measurements. By utilizing video recordings and similar tools, analysts have the advantage of reviewing the data multiple times, thereby enhancing accuracy and enabling a more comprehensive analysis of pedestrian flows (Greger and Wrede, 2019).

When measuring pedestrian flows and analyzing their movement patterns, it is crucial to consider various influential factors, including the time of day, trip purpose, land use, and site-specific characteristics (FHWA, 2016). In recent years, a range of innovative techniques have emerged to accurately calculate pedestrian flows. One notable method employed successfully in downtown Kristianstad involved the detection of mobile phones searching for WiFi. This system enabled the tracking and mapping of individuals' movements, providing valuable insights into walking patterns and flow dynamics. Additionally, cameras strategically placed within shopping centers and markets have proven effective in capturing people's movements and identifying their destinations or areas of interest. Leveraging advancements in technology, video analysis has become a very advanced method, as it is possible to remove the identities of people who have problematic morals (Greger and Wrede, 2019).

2.5.8 Pedestrian crosswalks

A policy to encourage walking in urban areas results in an increase in the number of crosswalks where people can safely cross and take priority over vehicular traffic (Knoop and Daganzo, 2018). A pedestrian crossing refers to a dedicated segment of the roadway that is purposefully designed to facilitate pedestrian movement across a street. Marked pedestrian crosswalks provide access to pedestrians and thus signal drivers to yield to pedestrians.

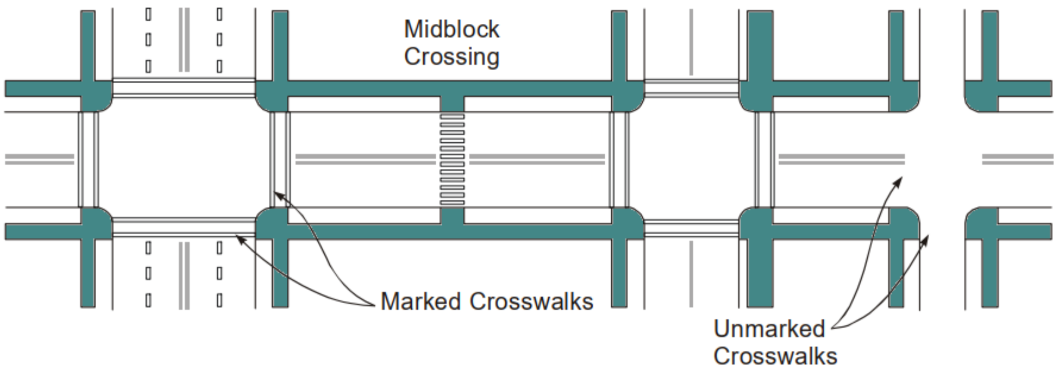

Figure 2.9 : Types of crosswalks.

Sometimes pedestrians may feel overly safe at these crossings to the point that they may put themselves in a dangerous situation with respect to vehicles in the false belief that the vehicle can stop. On the other hand, pedestrians' feelings of less safety at unmarked crossings cause them to be more cautious in waiting for safe gaps in traffic before crossing. In all cases, pedestrians are the most vulnerable users of the intersection, so pedestrian crosswalks must be designed to minimize pedestrian exposure to moving vehicles (Fitzpatrick et al., 2005; SMATB, OSMCC, 2018). Figure 2.9 illustrates examples of marked, unmarked, and midblock crosswalks.

2.5.8.1 Pedestrian crossing behavior

Pedestrian behavior at intersections is influenced by two crucial variables: time and distance (Malenje et al., 2018). In their pursuit of efficient travel, pedestrians seek to minimize waiting and crossing durations to conserve time and energy. To achieve this, pedestrians must carefully select their crossing location and adhere to existing barriers and crossing patterns. The choice of crossing route is contingent upon several factors, including the availability of gaps in vehicular traffic, the number of lanes to traverse, the speed of vehicles, and the direction of traffic flow. These considerations inform pedestrians' decision-making process as they navigate intersections, aiming to optimize their crossing experience while maintaining safety and expediency (Kadali and Vedagiri, 2013).

2.5.8.2 Improving pedestrian crossings

Pedestrian crosswalks play a critical role in guiding pedestrian movement through intersections, making it imperative to enhance their design to ensure optimal crossing conditions. Improvements to crosswalks should focus on various aspects, including enhancing crossing safety, reducing the distance pedestrians need to traverse, improving visibility for all road users, and minimizing conflicts between pedestrians, bicycles, and vehicles (NTMP, 2012; SOHDOT, 2013).

The presence of marked pedestrian crosswalks serves multiple purposes, including serving as a visual warning to drivers regarding the potential presence of pedestrians and indicating the designated area where pedestrians have the right of way. A comprehensive study conducted by the Federal Highway Administration examined the safety outcomes of marked and unmarked crosswalks at uncontrolled locations. The findings revealed that for two-lane roads, there was no significant difference in crash rates based on the presence or absence of a marked crosswalk. However, for multi-lane roads with an Average Daily Traffic (ADT) rating of 12,000 or higher, the presence of a marked crosswalk was associated with a higher rate of crashes. In such cases, additional enhancements such as overhead markers and refuge islands were recommended to improve safety. Refuge islands play a crucial role in reducing pedestrian exposure time by providing a safe area in the middle of the roadway, allowing pedestrians to focus on one direction of traffic at a time. Elevating the pedestrian crossing to align with the sidewalk level is another effective strategy to enhance visibility, encourage drivers to yield to pedestrians, and reduce vehicle speeds (Peers, 2019).

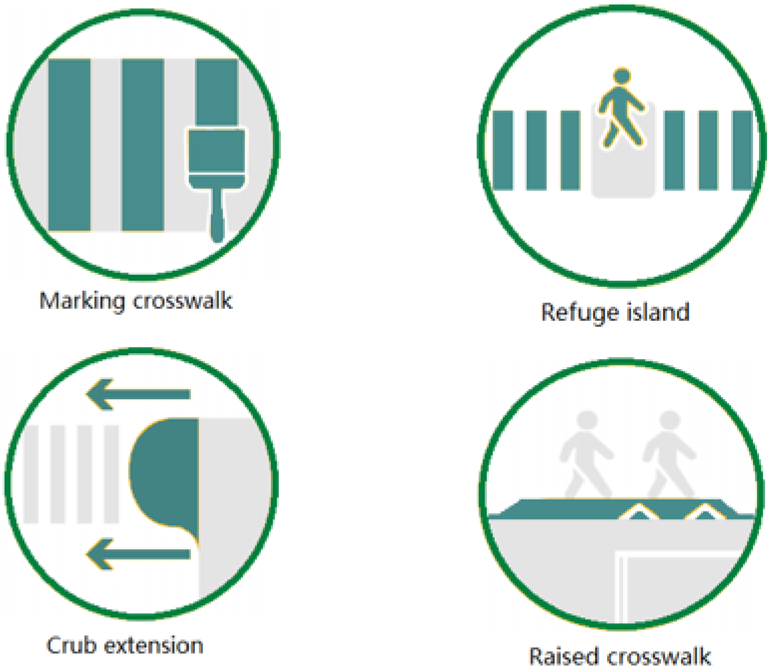

Figure 2.10 : Some ways to improve pedestrian crossings.

Reducing the pedestrian crossing distance leads to less time spent by pedestrians in the crosswalk, which enhances both their safety and the flow of vehicles and bicycles. Moreover, reducing pedestrian crossing distances contributes to increased green time for vehicles at signalized intersections. By implementing curb extensions, the length of pedestrian crossings can be shortened while also keeping parked vehicles clear of the crosswalks. This design approach provides pedestrians with better visibility of motorized vehicles and allows them to be more easily noticed by drivers before stepping into the crosswalk. Furthermore, the use of channelization islands and raised medians can effectively break up excessively long traffic lanes, enabling pedestrians to cross fewer lanes at a time. This facilitates a safer crossing experience, especially for slower pedestrians who can wait for gaps in traffic, thereby reducing potential conflicts and minimizing the overall distance they need to traverse (NTMP, 2012). Figure 2.10 displays various approaches to enhancing pedestrian crossings, illustrating potential improvements and design elements (Peers, 2019).

CHAPTER 3. INTERSECTIONS

3.1 Introduction

The infrastructure of road transportation networks is formed by the fact that traffic flows in different directions. Despite this fact, there is a demand for locations where they are able to interact. An intersection is defined as a shared area formed by the crossing or confluence of two or more roads, including facilities on either side of the road for traffic movements within the area, the primary purpose of which is to facilitate a change in lane directions (AASHTO, 2018). In other words, intersections are engineering structures built in areas where pedestrians and road vehicles meet on the same plane and safely pass each other on highways entering and exiting a city (Yayla, 2006).

Figure 3.1 : Lively intersection in an urban area.

Intersections are important and pivotal points in the transportation network, and they are where conflicts abound. This is a consequence of the fact that numerous traffic flows occupy this area concurrently, especially in urban road transportation axes such as the city center, where there is intense pedestrian mobility and an urban population that attempts to traverse these areas in order to reach their destination. Consequently, traffic management at intersections is critical in order to operate them efficiently and limit the danger of accidents. Intersections are designed to ensure the continuity of traffic flow, safety, and comfort in order to maintain impacts such as loss of time, fuel consumption, and exhaust gas emissions at an optimal level, as well as to eliminate negative situations such as reduced speed, prevention of traffic congestion and reduced travel times, queuing caused by increased regularity, and increased operating costs. Figure 3.1 illustrates a model of a lively intersection in an urban area.

3.2 Design Principles and Objectives

The intersection design must adhere to a set of fundamental design principles, which include speed reductions, lane alignments, and human factors considerations. Regardless of kind or location, the purpose of every intersection design should be to: Reduce vehicle speeds through the intersection as needed to achieve acceptable capacity, offer smooth and intuitive channelization for drivers, minimize conflicts between modes and unusual conflicts, accommodate all modes with suitable levels of service, and guarantee that the intersection is completely accessible (AASHTO, 2018; Kimley-Horn and Associates, 2015).

For pedestrians, many principles and important requirements must be fully considered in the design of intersections, including: crossings and pedestrian curb cut ramp locations; walking speeds on sidewalks and crosswalks; pedestrian flow capacity; traffic control yielding and delay. Furthermore, traffic control, operating speed, and bicycle capacity are important principles for bicycle accommodation (NTMP, 2012).

3.3 Design Considerations

The main function of intersection design is to facilitate safe and effective movements for all road users. The design of an intersection should be tailored to the operational characteristics of its users. According to AASHTO, the fundamental elements to take into account when planning intersections are as follows:

3.3.1 Human factors

The driver: The role of the driver is pivotal in the construction and operation of roads. The efficiency and safety with which drivers use the road determine the design's success. The driver should be able to interpret the crossing and the movements of the other vehicles. The designer of these intersection sites must constantly keep the user's limitations in mind, and the intersection design should meet the standards and codes based on which it is designed.

The pedestrian: Walking activity has an impact on the design and effectiveness of the intersection. The time at which they will cross the intersection, their physical ability, and age all affect the performance and design.

The cyclist: the experience, capabilities, and skills of the cyclist have a bearing on the design and efficiency of intersections. The design should be helpful for the cyclist in comprehending how to navigate the crossing.

3.3.2 Traffic considerations

To ensure the efficient functioning of intersections, a comprehensive array of factors is taken into account during the design process. These factors encompass roadway classifications, design and actual capacities, design-hour turning movements, traffic movements, vehicle speeds, transit involvement, crossing distance, crash history, bicycles, and pedestrian movements. Each of these elements plays a critical role in shaping the intersection's layout and functionality.

3.3.3 The physical environment

During the design process, special consideration should be paid to physical environmental aspects specifically in rural, urban, and industrial locations. Abutting properties, vertical alignments, sight distance, junction angle, conflict area, speed-change lanes, geometric design, traffic control, lighting, roadside design, environmental concerns, crosswalks, driveways, and access management are all aspects to consider.

3.3.4 Economic factors

The cost and anticipated benefits of renovations, the cost and effectiveness of controlling access points to adjacent residential or commercial properties, and energy consumption are all important economic factors in intersection design (AASHTO, 2018).

3.3.5 Occupational health and safety

Intersections should guarantee the safety and security of road maintenance employees and anyone who must perform occupational duties at or near intersections (Gary Veith and Owen Arndt, 2009).

3.4 Intersection Users

3.4.1 Motor vehicles

Since roadways are designed primarily to transport motor vehicles from their origin to their destination, they account for the great majority of intersection users. Passenger cars, mopeds, motorbikes, trucks, buses, and recreational vehicles are all considered motor vehicles. The physical and operational features of these vehicles must be considered in the design and operation of the intersection. By accounting for the specific requirements of each vehicle type, intersection designs can be optimized to accommodate the varied traffic flows, ensuring safe and efficient movements for all road users.

3.4.2 Pedestrians

Pedestrians are one of the main users of intersections, especially in urban areas and city centers. Pedestrians may cross at intersections in significant numbers depending on the surrounding land use and the presence or absence of bus stops. Different abilities, levels of experience, and walking speeds distinguish pedestrians. Hence The movement of pedestrians at intersections is of great importance due to its conflict with other traffic. The current designs for streets and urban roads provide an efficient network for transporting motor vehicles. However, most of the system is inaccessible to pedestrians.

3.4.3 Cyclists

Cycling for transportation is enjoying increased popularity, particularly in urban areas. as communities are recognizing the benefits of cycling for reducing congestion, improving air quality, and improving personal health (Weigand, 2008). Cyclists are also one of the intersection users, and their demands must be factored into intersection design (NTMP, 2012). Geometric design and signal phasing can help to prevent conflicts between bikers, pedestrians, and vehicles.

3.4.4 Transit

Buses, light rail, and heavy rail are all considered transit vehicles. Light and heavy rail both operate on a fixed guideway of two rails. Transit vehicles are often bigger than highway vehicles and have fewer stopping capabilities (Fitzpatrick et al., 2005). When used in transit operations, buses have the same fundamental qualities as vehicles. Furthermore, transit operations may include a transit stop at an intersection, affecting pedestrian, bicycle, and motor vehicle flow and safety (AASHTO, 2018).

3.5 Types of Intersections

Road intersections can be classified into two categories: at-grade intersections and grade-separated intersections, as illustrated in Figure 3.2. Grade-separated intersections allow free traffic to cross at different levels without interruption, which reduces the possibility of accidents or malfunctions at intersections due to the elimination of conflicts between different traffic movements. On the other hand, at-grade intersections do not offer separate levels for traffic movements, leading to potential conflicts between crossing traffic streams. As a result, at-grade intersections may experience more traffic-related challenges and safety issues compared to grade-separated intersections.

Figure 3.2 : Types of Intersections.

3.5.1 At-grade intersections

At-grade intersections take place when more than one route intersects at the same level. The shared area at these intersections is used sequentially by opposing streams at the same height and time, and the volume of traffic in the branches entering and exiting the intersection is treated with priority based on topographic conditions and pedestrian and vehicle safety regulations (Karayolları Genel Müdürlüğü, 2005).

At-grade intersections are classified according to the number of roads that comprise the intersection and the way these roads join; geometric design features; flare; and the type of control at the intersection.

3.5.1.1 Intersections according to cross-section

Intersections are classified according to their cross-section into two categories: simple intersections that keep the cross-section of the street throughout the intersection; and flared intersections that extend the cross-section of the street throughout the intersection.

Simple intersections

Simple intersections are those that keep an equal number of lanes throughout the intersection and are common in areas where no auxiliary lanes are required to deliver the appropriate level of service and in areas with low traffic volume. Pedestrian crossing distances at these intersections are available at a minimum (NTMP, 2012).

Flared intersections

Flared intersections are intersections characterized by an expansion of the cross-section of the street and an increase in the number of lanes to ease the turning movement. This type of intersection is common in high-traffic areas where it is flared to allow a left-turning lane, which removes left-turning vehicles from the traffic lane to increase capacity and maintain safety. A flare to the right is less commonly used and usually occurs on a large right-turning motion.

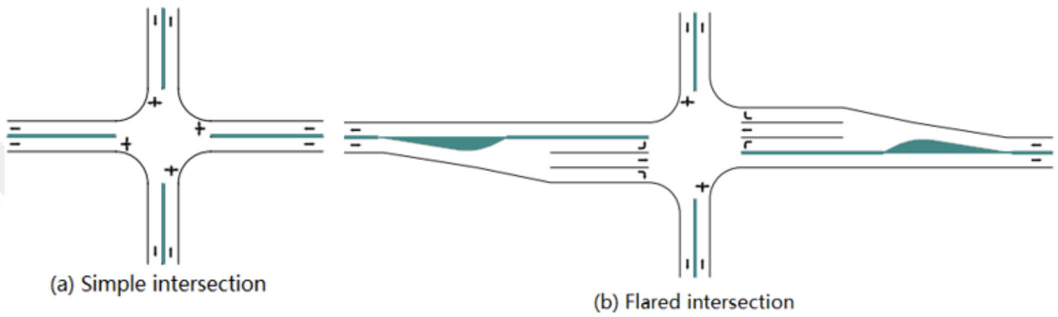

Figure 3.3 : Intersections according to cross-section.

The flare can be accommodated by an additional lane, and this approach is effective in increasing capacity in isolated rural or suburban environments. On the other hand, flared intersections increase travel time for pedestrians. Figure 3.3 shows a simple and flared intersection model (NTMP, 2012).

3.5.1.2 Intersections according to geometric design features

Intersections are classified according to geometric design features into channelized intersections that use signs and raised islands to designate the path of vehicles and unchannelized intersections that do not use signs and raised islands to direct the path of vehicles.

Channelized intersections

Channelized intersection is achieved by placing islands into the intersectional area, hence limiting the overall conflict area accessible. These islands assist in guiding, controlling, and constraining traffic to specified lanes. Additionally, they enable control over the speed and angle of approach for approaching vehicles, while effectively reducing areas of conflict within the intersection by isolating them from one another. The small and medium islands can be used efficiently as a pedestrian sanctuary and for the placement of signs and traffic control equipment (Rethaliya, 2017).

Channelized intersections are usually large, necessitating long pedestrian crosswalks. However, channelization islands can successfully lower the crosswalk distance at which pedestrians are exposed to moving vehicles. The demands of pedestrians must be considered in the design of channelized crossings, including pedestrian curb cuts or that provide wheelchair users with the same safe harbor as other pedestrians on channelization islands (NTMP, 2012).

Unchannelized intersections

The intersection area at these intersections is paved, and vehicles are not restricted from using any portion of the intersection area. They are the simplest to construct but the most complicated traffic operations, resulting in the greatest conflict area and the highest number of accidents. Figure 3.4 illustrates channelized and unchannelized intersection.

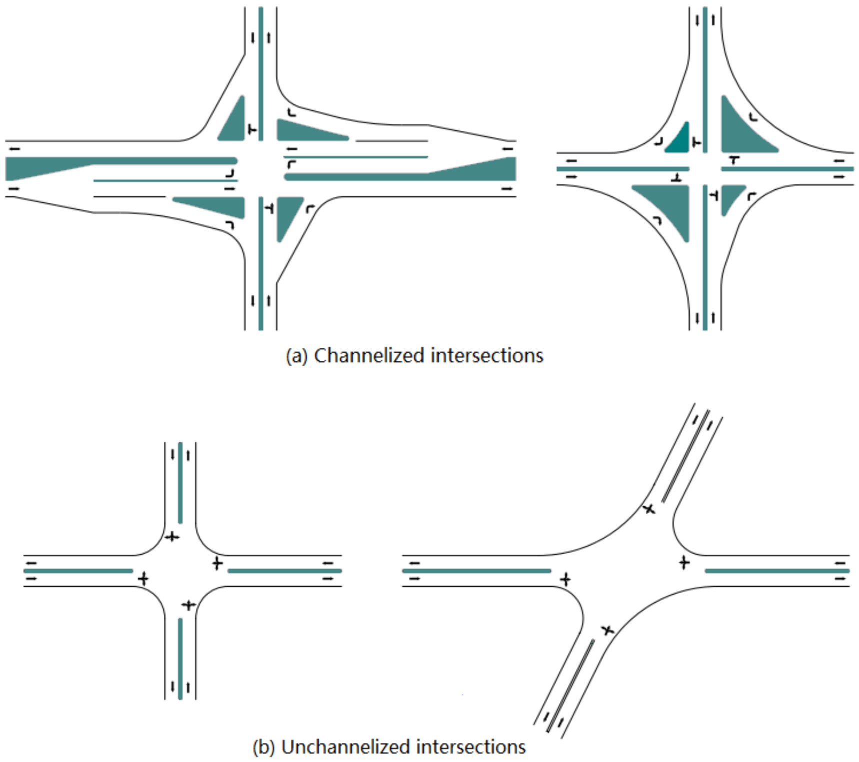

Figure 3.4 : Intersections according to geometric design features.

3.5.1.3 Intersections according to shape

Intersections differ according to the number of lanes converging at the intersection. Intersections are classified according to shape into three-leg, four-leg, and multileg intersections, in addition to circular intersections.

Three-leg intersections

The prevalent forms of three-leg conventional junctions are T, Y, and skewed intersections. Unchannelized three-leg intersections are ideal for minor or local roads and may be utilized where minor roads intersect important highways with an intersection angle of not generally more than 15 degrees from perpendicular. This type is also appropriate for rural two-lane roads with light traffic. Where speeds or turning movements, or both, are high, an additional surface width or flaring may be provided for maneuverability (AASHTO, 2018; Nicholas J. Garber, 2009). Figure 3.5 illustrates unchannelized three-leg intersections.

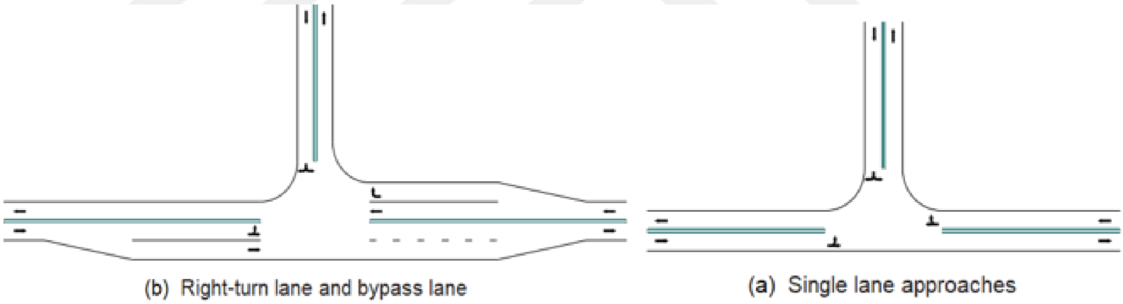

Figure 3.5 : Unchannelized three-leg intersections.

Three-leg intersections also exist with channelization. Where channelization is offered, islands and turning lanes should be planned to accommodate each vehicle's wheel tracks while providing optimal crossing pathways and storage for pedestrians inside the proposed intersection. As illustrated in Figure 3.6a and Figure 3.6b, the simplest type of channelization is achieved by expanding the corner radius between the two roadways sufficiently to provide a distinct turning roadway that is isolated from the normal traveled ways of the intersecting approaches by an island. The strategic use of channelization elements optimizes traffic flow and ensures smooth interactions between road users (AASHTO, 2018).

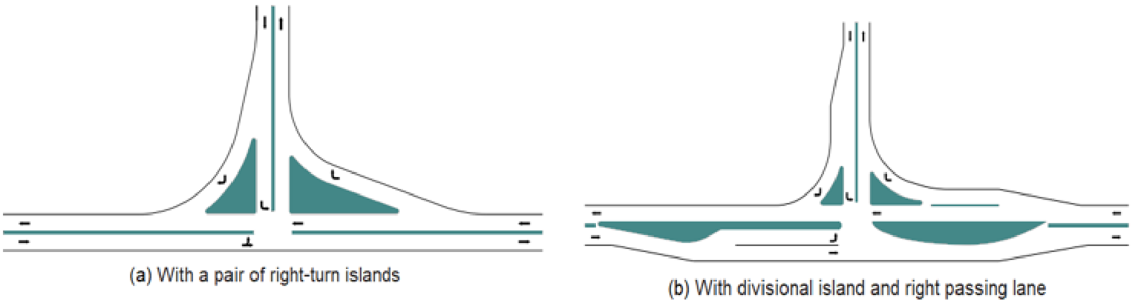

Figure 3.6 : Channelized three-leg intersections.

Four-leg intersections

Four-leg intersections are the most prevalent type of intersection. The unchannelized intersection illustrated in Figure 3.7a is typically utilized at locations of minor or local roads, although it may also be used where a minor road intersects a large highway. Turning volumes are typically low in these circumstances, and the roads cross at an angle of no more than 30 degrees from the perpendicular. In scenarios with frequent right-turning movements, right-turning roadways, as illustrated in Figure 3.7b, can be implemented to accommodate these specific traffic patterns.

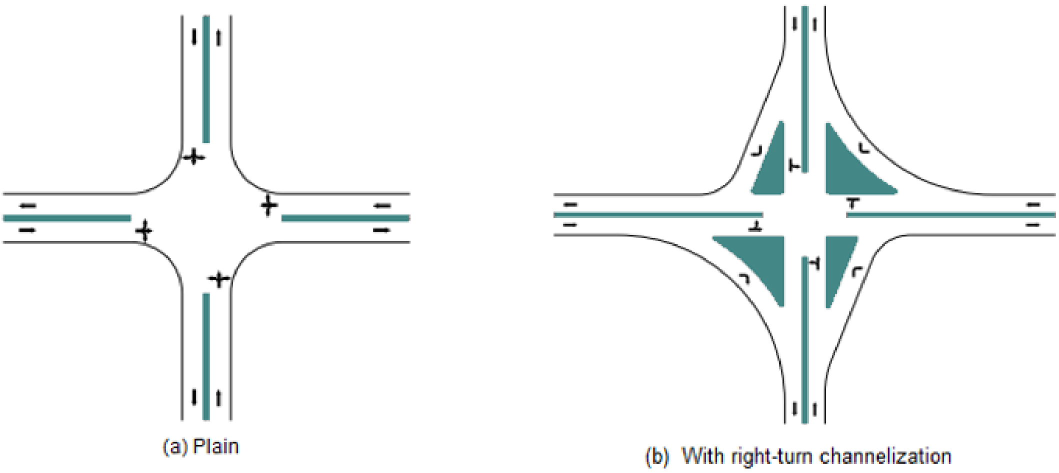

Figure 3.7 : Four-leg intersections.

Multileg intersections

Multileg intersections are produced by the confluence of five or more approaches and are formed in low-traffic areas where there is a controlled stopping (Karayolları Genel

Müdürlüğü, 2005). These intersections offer a complex layout with multiple roads intersecting, requiring careful traffic management and control.

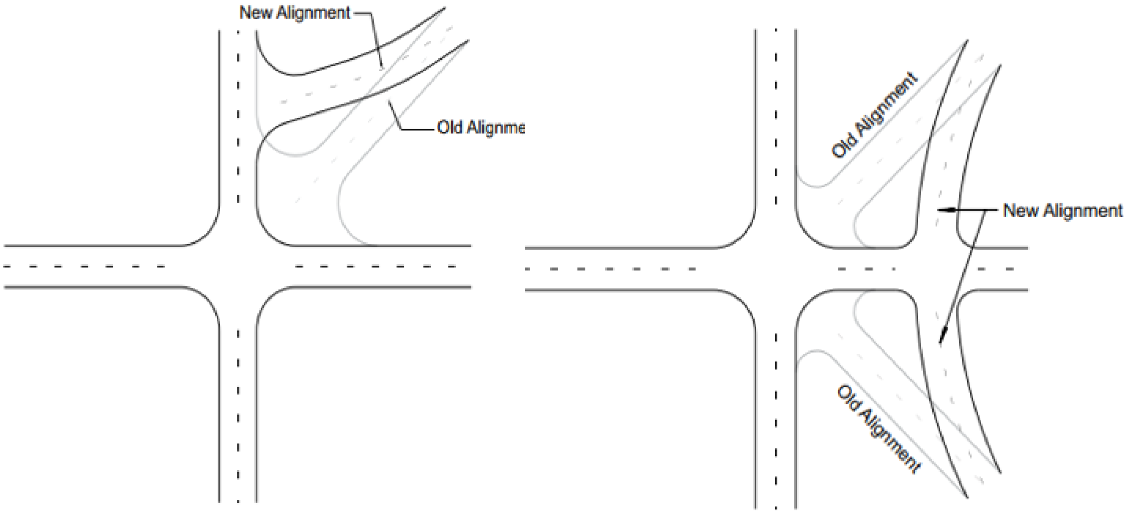

Figure 3.8 : Multileg intersections.

This type of intersection is operationally undesirable and should be avoided by realigning one or more crossing legs and merging certain traffic movements at neighboring subsidiary intersections, in order to remove some opposing traffic from the main intersection and improve safety and efficiency, as shown in Figure 3.8 (AASHTO, 2018).

Circular intersections

Circular intersections are a special form of at-grade intersection designed to enable traffic to move in one direction around a central traffic island (AASHTO, 2018; Mathew, 2006). According to another definition, circular intersections are a type of controlled intersection established by altering the operating style of the traffic at the intersection as a result of the physical design of the intersection in a different geometry rather than with lighting and electrical systems such as signalization (Karayolları Genel Müdürlüğü, 2005).

In these kinds of intersections, essentially, all large conflicts at an intersection, such as the collision of through and right-turn movements, are turned into milder conflicts, such as merging and diverging. The vehicles entering the circular intersections are gently urged to travel in an orderly anticlockwise pattern. They then exit the rotary in the desired direction (Mathew, 2006). The Federal Highway Administration document specifies three forms of circular intersections: rotaries, neighborhood traffic circles, and roundabouts.

Rotaries have huge diameters, often bigger than 100m, permitting speeds in excess of 50 km/h. They often provide little or no horizontal deviation of through traffic pathways and may even follow the traditional "yield-to-the-right" norm, in which circulating traffic gives way to incoming traffic.

Neighborhood feature substantially smaller diameters than rotaries, allowing for much slower speeds. As a result, they are mostly employed at minor street crossings as a traffic calming and/or aesthetic feature. The intersection approaches might be uncontrolled or regulated by a stop sign.

Roundabouts are a type of circular intersection with a special design and traffic control features in several ways, including yield control of all approaching vehicles, elevated islands, and a proper design of curvature to allow speeds on the circulatory roadway of less than 30 km/h (Robinson et al., 2000).

According to size and number of lanes, modern roundabouts can be classified into mini-roundabouts, single-lane roundabouts and multilane roundabouts. Figure 3.9 shows the a type of modern roundabout (multilane). Each type of roundabout serves specific traffic needs and capacities.

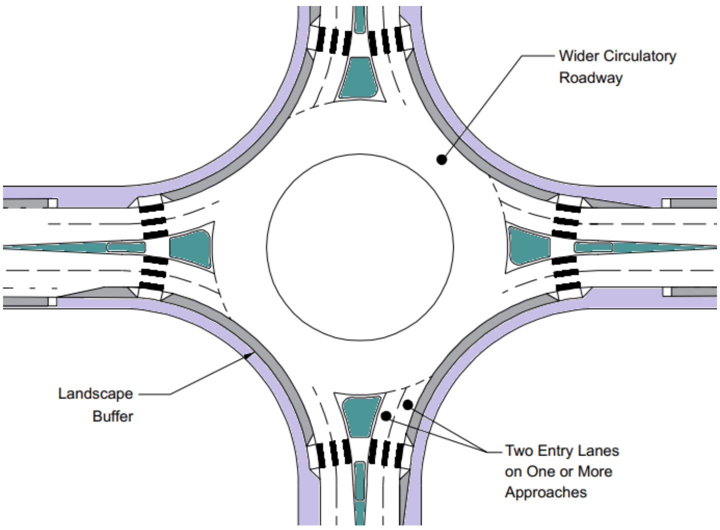

Figure 3.9 : Typical multilane modern roundabout.

3.5.1.4 Intersections according to traffic control

The intersections are classified according to the type of control into signalized (where traffic is controlled by a light signal), non-signalized (where traffic is controlled by yield signs, stop signs, or the driver of a vehicle approaching an intersection should be able to see potentially conflicting vehicles in sufficient time to stop before reaching the intersection). Figure 3.10 shows Intersections according to traffic control.

Signalized intersections

Signalized intersections are intersections or crossing points where traffic and pedestrians move in any direction and in any sequence in a regular and safe manner (AASHTO, 2018). They are controlled by specific lighting equipment, giving drivers less freedom. These intersections are located on high-traffic roads and are designed to regulate vehicle and pedestrian flow at intersections on a regular basis. As a result, it excludes the number of accidents that may occur as a result of vehicles and pedestrians interacting at the same level, as well as other disadvantages such as intersection congestion. This system also enables pedestrians and cyclists, who are vulnerable traffic users in urban road networks, to travel more safely inside the system.

The necessity of signal-controlled intersections comes when traffic congestion increases at unsignalized at-grade crossings. Their performance begins to deteriorate when the intersection hits capacity. Because such intersections can achieve a consistent flow, safety improves as capacity grows, and traffic accidents decrease dramatically (Yayla, 2006). However, it has been discovered that when control is supplied with signals, rear-end collisions rise, and if the signal phase diagram is not accurately estimated, intersection performance drops much more than previously.

Unsignalized intersections

Unsignalized intersections are a typical feature of urban traffic; these intersections function without the use of a signaling system, allowing a few vehicles to disregard traffic directions in order to pass the intersection as rapidly as possible. Such behaviors have the potential to lead to numerous traffic congestions and vehicle accidents.

Vehicles approaching this junction must follow basic traffic regulations and give priority to one vehicle, often those on the main route (Fan et al., 2014).

Traffic control at unsignalized intersections is carried out in three different ways:

Uncontrolled: These intersections are characterized by the absence of any traffic control measures or signals regulating the approaches to the intersection. In this scenario, drivers approaching the intersection must rely on their own judgment and observation to navigate safely. Uncontrolled intersections are common in rural and residential regions with low traffic volumes (AASHTO, 2018).

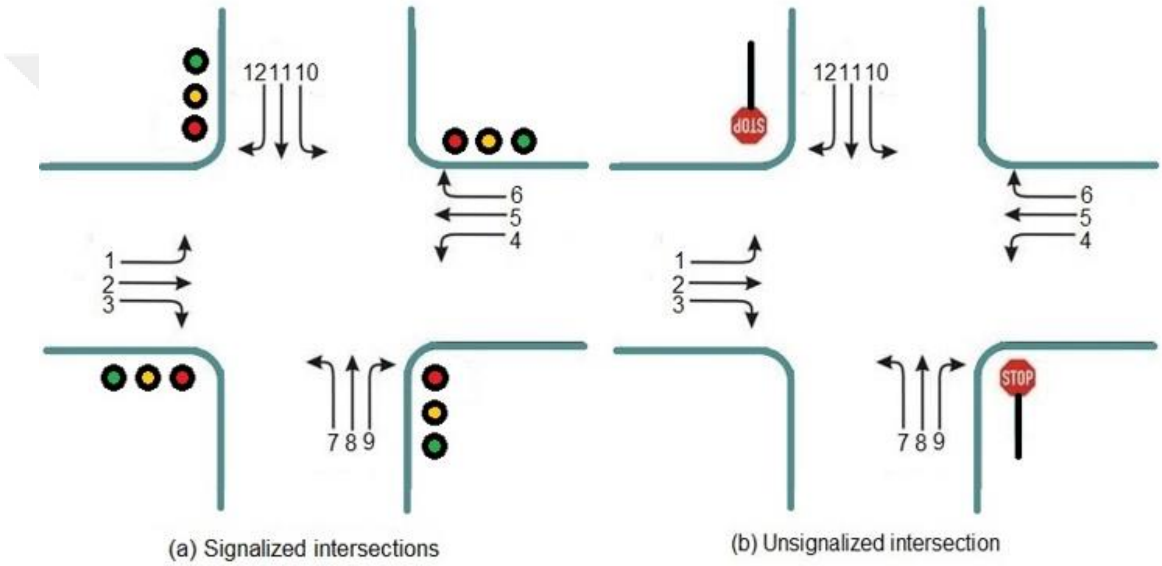

Figure 3.10 : Intersections according to traffic control.

Give way control: At intersections with give way control, one or more arms of the intersection are regulated by "Give Way" signs. These signs are typically used to govern minor routes or circular intersections.

Stop control: Intersections with stop control require vehicles on the secondary road to come to a complete stop before crossing onto the main road. "STOP" signs are placed on the sides of the secondary road to indicate this requirement. This type of control is typically used at intersections where the main road has substantially higher traffic volume than the secondary road.

3.5.2 Grade-separate intersections (Interchange)

An interchange is a network of interconnected roadways with one or more grade dividers that use tunnels and bridges to shift traffic flows between two or more freeways to different levels. Interchanges provide sufficient capacity to accommodate high volumes of traffic safely and effectively. The purpose of interchanges is to decrease confrontations between vehicles, pedestrians, and cyclists at intersections (AASHTO, 2018). They are also the most efficient solution for avoiding accidents and delays, but in poor terrain, they are prohibitively expensive, and in regular terrain, they may result in undesirable peaks and slopes (Nicholas J. Garber, 2009; Yayla, 2006).

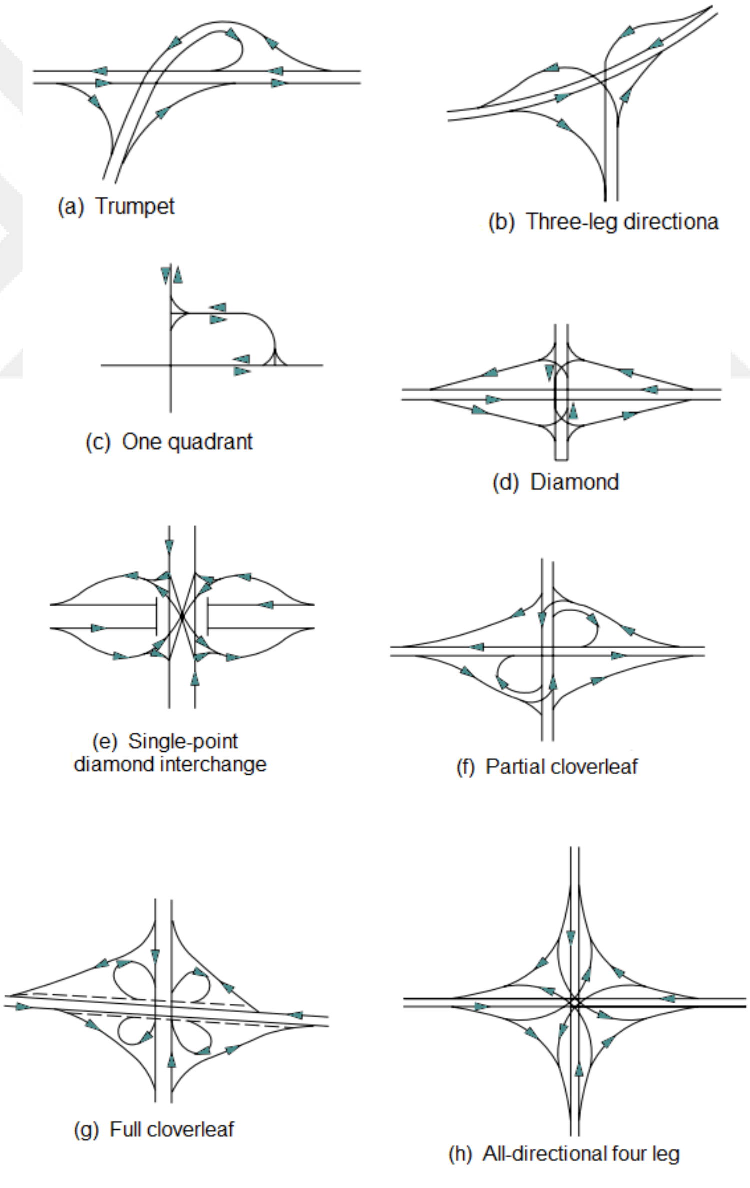

Figure 3.11 : Classifications of interchanges.

Figure 3.11 shows many classifications of interchanges according to the number of legs, the method of connection, and the shape (trumpet, three-leg directional, one quadrant, diamond, single-point diamond, partial cloverleaf, full cloverleaf, all-directional four-leg).

3.6 Traffic at Intersections

Intersection traffic constitutes the most challenging and complex area on any road. There are too many conflict areas at intersections because vehicles traveling in opposite directions seek to share the same space. Pedestrians also want to be able to cross in the same area. Navigating through an intersection demands quick decision-making from drivers, as even the smallest error can lead to severe accidents. The complexity of intersections can cause delays and is influenced by various factors, including the intersection's geometry and type of traffic control. The performance of intersections has a direct impact on overall traffic flow and significantly influences road capacity, especially in urban environments where traffic density is higher (Mathew, 2006).

3.6.1 Intersection traffic conflicts

Conflicts at intersections arise when the paths of vehicles intersect, merge, or diverge. These points of interaction also encompass situations where vehicles cross paths with pedestrians or bicycles. The presence of conflicts at intersections underscores the need for careful planning and efficient traffic management to ensure the smooth and safe flow of all road users.

3.6.1.1 Vehicle conflicts

Conflicts are categorized according to the degree of severity into three main categories: queuing conflicts, merging or divergent conflicts, and crossing conflicts. Queueing conflicts, which are the least dangerous because there is a difference in speed and they are in the most protected parts of the vehicles, occur when the vehicle hits the back of the queue when approaching it. Merger and divergence conflicts come to a higher degree due to the possibility of collision on the side of the vehicle, and these conflicts occur when two streams of traffic flow merge or separate. Crossing conflicts, which are the most dangerous and common of all conflicts, occur at the crossing of two streams of traffic flow (Robinson et al., 2000).

Figure 3.12 shows a four-leg cross intersection and a four-leg roundabout. As shown in the figure, the number of vehicle-vehicle conflict points for roundabouts falls from 32 to 8 for four-leg intersections.

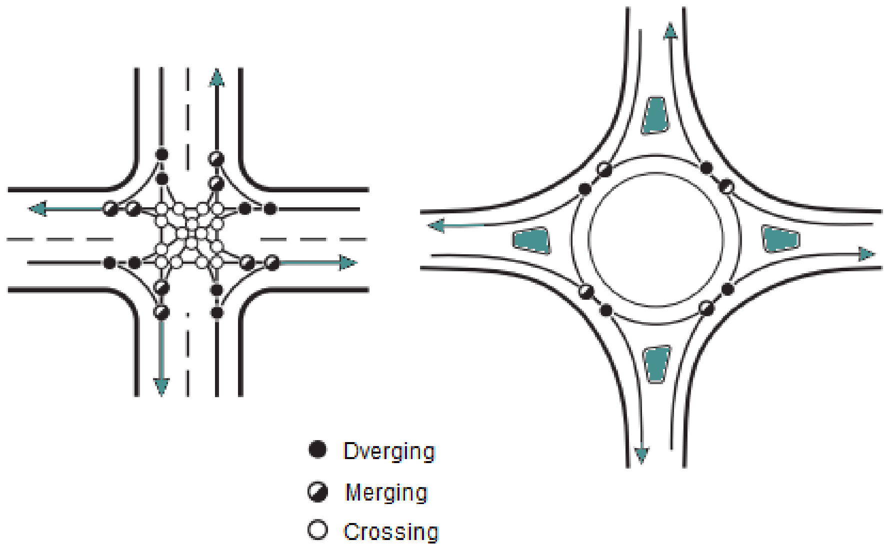

Figure 3.12 : Vehicle conflicts.

3.6.1.2 Pedestrian conflicts

Pedestrian and vehicle conflicts occur at all sorts of intersections, regardless of pedestrian volume. Figure 3.13 shows potential pedestrian-vehicle conflicts at intersections. Signalized intersections with signal phases that only allow a few vehicles to legally move at any one time provide an opportunity to reduce the potential for vehicle and pedestrian conflicts. Pedestrians at this type of intersection encounter four opposing vehicle movements, which get progressively worse as extra approaching lanes are implemented. On the other hand, pedestrians at roundabouts encounter two opposing vehicular movements at each approach. When a roundabout intersection has multiple approach lanes, pedestrians face additional conflicts with each supplementary lane they must cross, making the task of safely navigating through the intersection more demanding (Robinson et al., 2000).

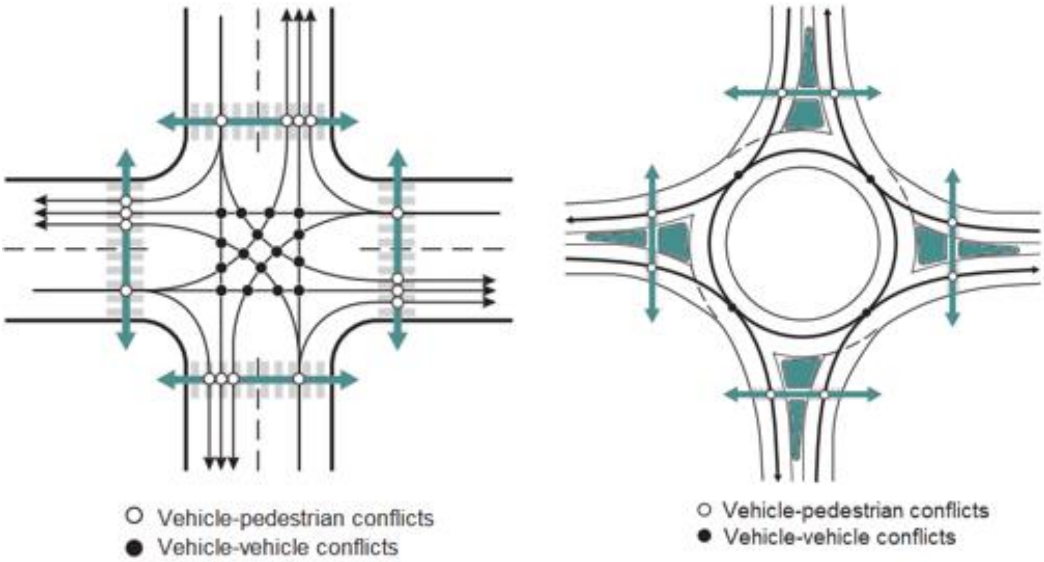

Figure 3.13 : Pedestrian conflicts.

3.6.2 Intersection traffic control

There are various techniques or levels of vehicular cross-flow control at intersections in use, which can be passive, semi-control, or active. The choice of one of these levels depends on the type of intersection and the volume of traffic in each of the opposing streams (Mathew, 2006).

3.6.2.1 Passive control

Passive control is control in which the driver is not subjected to such rigorous standards. The intersection control that falls under passive control is classified as follows:

No control: In the lack of control devices, if traffic approaching an intersection is limited, the driver on the left must yield to the driver on the right when the vehicle on the right is approaching in a dangerous manner. In essence, the vehicle on the left is in charge of avoiding a possible confrontation (Roger P. Roess, Elena S. Prassas, 2016). According to AASHTO, to ensure safe operation in the absence of control, both drivers should be able to stop before reaching the collision site when they first see each other.

Traffic signs and marking: They are warning and guidance signs that enforce a certain degree of traffic control at intersections. Stop lines, yield lines, and arrow markings are some examples (Mathew, 2006).

Yield control: Vehicles approaching an intersection with yield signs are obligated to slow drastically and give way to all conflicting vehicles. While coming to a complete stop at yield signs is not mandatory, drivers must pause when necessary to avoid impeding the flow of traffic that has the right of way. Yield signs are typically installed on side roads approaching intersections to promote a safe and orderly traffic flow, encouraging drivers to slow down and allow vehicles on the main route to proceed without interruption (Roger P. Roess, Elena S. Prassas, 2016).

Stop control: A stop control is used to force approaching vehicles to stop before entering an intersection. Stop control remains a controversial form of control. While some agencies view it as an effective safety measure, others argue that the potential confusion and inconvenience caused by frequent stops might outweigh its benefits (Roger P. Roess, Elena S. Prassas, 2016). Stop control can be classified into two types: Two-way stop control, where drivers on minor streets yield to avoid conflicts, and multiway stop control, where all vehicles approaching the intersection are required to stop before proceeding. Multiway stop control is typically employed when traffic volumes on all intersecting roads are high and relatively equal, ensuring safer and more orderly traffic movements at busy intersections.

3.6.2.2 Semi control

In semi-control, the traffic agency has some control over the driver. Channelization and roundabouts come as semi-control.

Channelization: A channelized intersection is a type of intersection design that incorporates elevated barriers or solid white lines to guide traffic within designated lanes, facilitating safe and efficient movements at complex intersections. By effectively directing the flow of vehicles, these barriers significantly reduce potential conflicts in traffic, enhancing overall intersection safety (Nicholas J. Garber, 2009).

Roundabouts: roundabout, or rotary, is a form of intersection control that permits traffic to flow in one direction around a traffic island. Drivers approaching the roundabout must see potentially conflicting vehicles in order to decide when they may advance to the roundabout (AASHTO, 2018).

3.6.2.3 Active control

There are no maneuvers in active control; vehicles must stick to the regulations and lanes established by traffic control authorities. Traffic signals and interchanges are instances of this control.

Traffic signals: Traffic signal control depends on time sharing, in which some traffic is restricted to enable others to flow. The volume of approaching traffic at an intersection is the most crucial factor in determining the necessity for traffic signals, although pedestrian volume and collision experience may also play a significant role (Nicholas J. Garber, 2009). Traffic signals should only be used when the intersection complies with the Manual on Uniform Traffic Control Devices (MUTCD) requirements. Traffic signals help to keep traffic flowing orderly, increase the traffic capacity of the intersection, and reduce the frequency and severity of collisions, especially right-angle collisions. On the other hand, delays, excessive disobedience to the signal and the frequency of rear-end collisions are increased (FHWA, 2009).

Interchange: Interchanges are the most expensive type of control and are used in high-speed facilities to provide traffic flow at different levels.

CHAPTER 4. TRAFFIC PERFORMANCE METRICS AT INTERSECTIONS

4.1 Introduction

The procedure for assessing the performance of a certain intersection is meticulous and unreliable. The intersection may be in good condition for vehicles, but it is dangerous for other road users, such as pedestrians and cyclists. Performance metrics should take an integrated, holistic approach to the goals and behaviors of everyone using the intersection from the perspectives of safety, design, and economy.

4.2 Vehicle Performance Metrics

According to the user perspective, there are diverse metrics for assessing the performance of vehicle traffic at intersections, including fundamental performance metrics such as delay, level of service, queue length, and number of stops. Fuel consumption, pollutant emissions, and cost are some other secondary metrics of performance.

4.2.1 Travel time and delay

Travel time at an intersection determines the duration of time desired to travel from one point to another at an intersection. When performing travel time studies, data may be gathered on the locations and motives behind delays, which are caused either by engineering design or traffic conditions. Delays are considered the most common measure used to describe the operational quality at intersections. The delay and travel time data at a particular intersection give a good indication of the vehicle and pedestrian traffic as well as the quality of service at that intersection, and this data aids in the resolution of issues in order to enhance the flow and movement at the intersection (Nicholas J. Garber, 2009). Urban roads, especially intersections, are areas with high traffic volumes for vehicles and pedestrians, and the inevitable result is delays and congestion if not properly designed, which call for a free and smooth flow and traffic safety for vehicles and pedestrians.

A vehicle delay is defined as the time a vehicle loses in traffic for reasons not caused by itself. Delay is more precisely described as the time gap between a driver's desired and actual travel time. The delay experienced by vehicles at signal intersections is defined as the disparity in time between the real time the vehicle spends at the intersection and the travel time when there is no control of traffic lights at the intersection or fluctuations in speed (Koonce et al., 2008). In traffic research, delay is an important indicator of efficiency, as it includes both the direct cost of fuel consumption and emissions and the indirect cost of wasted time for drivers, as well as detrimental health effects due to traffic-related pollution (Bivina et al., 2016).

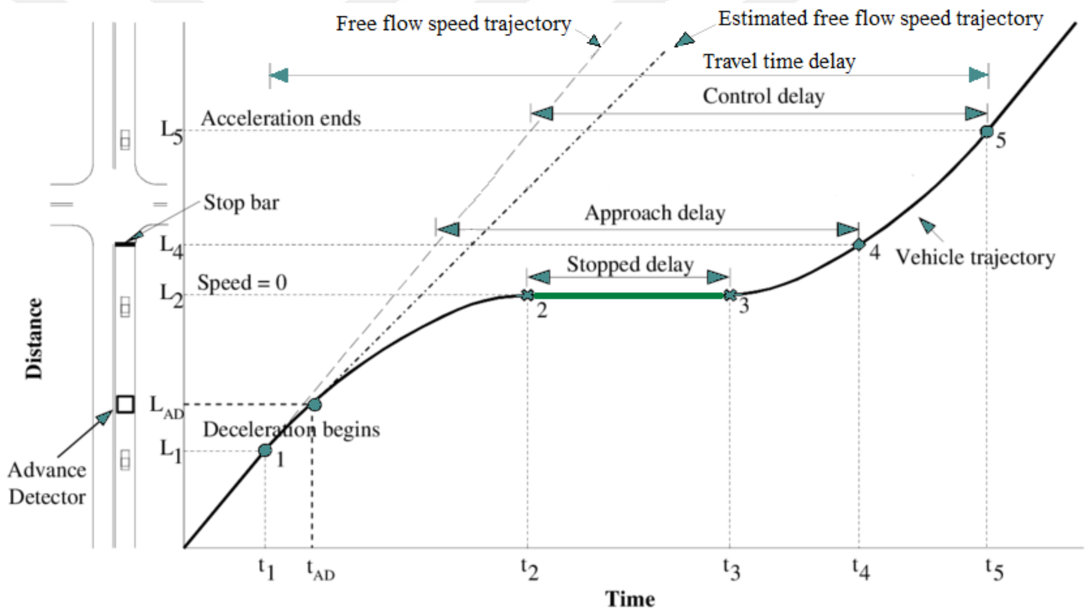

Figure 4.1 : Forms of vehicle delays at intersection.

Vehicle delays come in many different forms that can be summarized as follows:

Stopped delay: This delay is defined as the time a vehicle spends waiting at a stop line or queue to cross an intersection, and is taken over a period of time as an average of all vehicles.

Approach delay: The approach delay includes the stopping delay plus the time that the vehicle takes to slow down and approach to stop and re-accelerate to reach the desired speed, and it is determined within a certain time as an average for all vehicles.

Time-in-queue delay: It is the complete time consumed by the vehicle from the moment of joining the queue at the intersection until crossing and unloading from the stopping line upon departure. It is also taken as an average over a specified period for all vehicles.

Travel-time delay: This type of delay represents the difference between the expected time for a vehicle to pass through an intersection when drivers are moving at their desired speed without any obstacles, and the actual travel time experienced by the vehicle. However, due to the difficulty in accurately identifying this delay, as it depends on drivers' individual preferences for roads and their travel times, it is rarely used in practice.

Control delay: This delay is the most widely used in studies and is defined according to HCM as the delay caused by control devices, whether traffic lights or stop signs and give way. It is almost the result of adding the time taken to accelerate and decelerate to the time-in-queue delay (HCM, 2010b; Roger P. Roess, Elena S. Prassas, 2016). Figure 4.1 shows all types of delays in a time-space graph.

Numerous techniques and methodologies have been developed to compute delay at signalized and unsignalized intersections, including the HCM Formula, the Webster Formula, and the Australian Formula, as delay plays a crucial role in assessing the performance at intersections. However, for the purposes of this study, which focuses on unsignalized intersections, it is sufficient to mention the technique used to estimate delay at these intersections.

The average control delay of vehicle traffic for roundabouts is generally identical to that used for other unsignalized intersections, which hinges on approach capacity and saturation degree. The Highway Capacity Manual (HCM) provides Equation 4.1 as an estimate of the average control delay per lane for a roundabout entrance, assuming no queue at the start of the analysis period. However, if the demand exceeds capacity during the analysis period, it may result in a queue at the beginning of the time period, thereby rendering the delay calculated by this method inaccurate (HCM, 2010b). Proper consideration of these factors is essential to obtain accurate delay estimates for roundabouts and other unsignalized intersections in traffic engineering analyses.

$$d = \frac{3600}{c} + 900T\left((x-1) + \sqrt{(x-1)^2 + \frac{\left(\frac{3600}{c}\right)x}{450\,T}}\right) + 5 * \min(x, 1) \qquad (4.1)$$

Where,

d = average control delay (s/veh),

x = volume-to-capacity ratio of the subject lane,

c = capacity of the subject lane (veh/h), and

T = time period (h) (T = 0.25h for a 15-minanalysis).

At STOP-controlled intersections, the same Equation 4.1 is used, except the addition of "+5", which takes into account the YIELD control that permits drivers to cross without coming to a complete stop in the absence of conflicting traffic.

4.2.2 Queue length

Vehicle queuing is an important factor in evaluating performance and efficiency at intersections, and it should be considered as part of the intersection analysis. Estimates of vehicle queuing are critical for determining the amount of storage necessary for turning lanes and if extension happens at upstream facilities (lanes, unmarked intersections, flagged intersections, etc.). There could be a noticeable increase in rear-end collisions on approaches facing long queues. Vehicle queues are commonly predicted using the expected 95th percentile queue during the design period, which is the length that has only a 5-percent probability of being exceeded during the analysis time period. (Chandler et al., 2013).

For design purposes, Equations 4.2 and 4.3 are used to estimate the 95th percentile queue at roundabouts and unsignalized intersections respectively. However, it is important to note that these equations are valid only when the volume-to-capacity ratio just before and after the study period is less than 0.85, indicating that any remaining queues would be negligible. These estimation procedures follow guidelines from the Highway Capacity Manual (HCM) and other relevant studies (HCM, 2000, 2010b; Robinson et al., 2000).

$$Q_{95} = 900T\left(x - 1\sqrt{(1-x)^2 + \frac{\left(\frac{3600}{c}\right)x}{150T}}\right)\left(\frac{c}{3600}\right) \quad (4.2)$$

$$Q_{95} \approx 900T\left(x - 1\sqrt{(x-1)^2 + \frac{\left(\frac{3600}{c}\right)x}{150T}}\right)\left(\frac{c}{3600}\right) \quad (4.3)$$

Where,

Q_{95} = 95th percentile queue (veh),

x = volume-to-capacity ratio of the subject lane,

c = capacity of the subject lane (veh/h), and

T = time period (h) (T = 1 for a 1-h analysis, T = 0.25 for a 15-min analysis).

4.2.3 Number of stops

Intersections represent key locations where frequent vehicle stops occur due to the presence of control devices that regulate traffic flow by managing conflicting vehicle paths. The number of stops can be defined as the number of stops per vehicle, even though there is no reason to stop (public transit stops or parking lots). Australian road research board defines the stop rate as the average number of complete stops per vehicle, which may be determined at isolated fixed-time signals using Equation 4.4.

$$h = 0.9\left(\frac{1-u}{1-y} + \frac{N_o}{qc}\right) \quad (4.4)$$

Where

h = the stop rate,

u = green time ratio,

y = flow ratio,

No = average overflow queue in vehicles and

qc = average number of arrivals in vehicles per cycle.

Stopping is one of the causes of delay and has a cost relationship related to fuel consumption and vehicle wear, so knowing the number of stops assists in evaluating the traffic of vehicles and computing the cost for road users (Akçelık, 1981).

4.2.4 Level of service (LOS)

Level of Service (LOS) is a descriptor that connects relative operational quality (based on specific measures of effectiveness) to the degree of driver perception in a simple way, and is one of the primary criteria for evaluating performance in intersection traffic (Chandler et al., 2013). The Highway Capacity Manual has termed levels of service (LOS) as "qualitative measures that characterize operational conditions within a traffic stream and their perception by motorists and passengers". Speed, journey time, maneuverability, traffic snarls, convenience, and accessibility are all considered in LOS (HCM, 2010b). To describe the LOS for the entire intersection or each intersection approach, the average control delay and volume-to-amplitude ratio are used, where the delay determines the increase in travel time due to traffic controls (STOP, YIELD, or SIGNALS). It is also an alternative measure of driver harassment and fuel consumption (HCM, 2010b; NTMP, 2012).

The quality of traffic at the intersection is graded into six levels, ranging from Level A, which symbolizes a smooth traffic flow, where the driver of the vehicle is completely free and comfortable to drive at the required speed or higher than the declared speed, to Level F, which symbolizes the worst quality in the flow of traffic. The criteria for determining the level of service for vehicles at intersections are shown in Table 4.1 In the case of unsignalized intersections and roundabouts, if the facility is operating at a volume-to-capacity ratio and the ratio exceeds one, the facility is automatically granted LOS F, regardless of the estimated delay.

LOS serves as an essential tool for transportation planners and engineers to assess intersection performance, aiding in the design of efficient and well-functioning roadways, enhancing overall traffic flow, and ensuring a positive experience for drivers and passengers alike.

Table 4.1 : Vehicle level of service (LOS) at intersections.

LOS Measure	Intersection Type		
	Signalized Intersection Delay[1] (s)	Unsignalized Intersection[2] Delay (s)	Roundabout[2] Delay (s)
A	≤ 10	≤ 10	≤ 10
B	> 10-20	> 10-15	> 10-15
C	> 20-35	> 15-25	> 15-25
D	> 35-55	> 25-35	> 25-35
E	> 55-80	> 35-50	> 35-50
F	> 80	> 50	> 50

Source: Highway Capacity Manual, (HCM 2010) Transportation Research Board, 2010.

1 Delay is "control delay" as defined in HCM 2010, and includes time for slowing, waiting in queues at the intersections, and accelerating back to free-flow speed.

2 If the v/c ratio of the intersection being analyzed exceeds 1.0 the LOS is automatically F regardless of delay.

4.2.5 Environmental impact

Road vehicles are significant contributors to environmental pollution, emitting various harmful compounds that cause damage to the environment. Among these emissions, carbon monoxide (CO) is a notable pollutant that persists in the atmosphere for an extended period, with over 70% of its global production originating from the transportation sector. In addition to nitric oxide (NO), nitrogen dioxide (N2O), and other pollutants that cause air pollution by reacting with carbon dioxide and nitrogen oxides in the atmosphere in the presence of sunlight, forming photochemical smoke that contains ozone (Pomykala, 2018). According to the Australian Road Research Board (ARRB), fuel consumption, polluting emissions, and cost can be found based on total delay and number of stops as shown in Equation 4.5.

$$E = f_1 C + f_2 D_s + f_3 H \tag{4.5}$$

Where,

E = the statistic of interest e.g fuel consumption (L/h),

C = total amount of travel (= cruising distance x flow) in (veh-km/h),

Ds = total stopped delay time in (veh-h/h),

H = total number of complete stops per hour, and

f_1, f_2, f_3 = factors average rate for cruise, delay and stops, respectively.

4.3 Pedestrian Performance Metrics

It is important to assess pedestrian movement, especially at intersections, in order to enhance walking, develop effective solutions to walkability needs, improve safety, and provide better level of service. Traffic departments and many agencies use multiple performance metrics to assess pedestrian movement, such as delay, travel time, density, number of stops, and level of service, to improve safety, health, and access to an integrated pedestrian environment.

4.3.1 Travel time and delay

Travel time is a crucial metric that quantifies the average duration taken by road users, including pedestrians and cyclists, to cover a specified distance. As a performance measure, it enables the estimation of travel time for various modes of transportation to traverse a specific segment or a typical trip. In some contexts, it may be advantageous to define a typical trip in a specific time period, being careful not to specify peak demand. Calculating travel time involves considering average travel speeds and estimating intersection delays (Semler et al., 2016).

On the other hand, delay refers to the additional travel time experienced by drivers, passengers, pedestrians, or cyclists when traveling at their desired speed (HCM, 2010b). For pedestrians, delay encompasses any time spent waiting to cross, whether it be at the curb or on a refuge island. Multiple factors contribute to pedestrian delays, including signal delays, congestion-induced delays, road layout complexities, and the acceptance of traffic gaps (Semler et al., 2016). Understanding and minimizing delays for all road users are essential aspects of optimizing intersection performance and ensuring efficient and safe mobility.

Pedestrian delays at crossing locations are a significant aspect of urban traffic planning and assessing enhancements to pedestrian crossing facilities utilizing traffic signal controls. Furthermore, the accurate identification of these delays helps with the correct selection of appropriate treatments for pedestrian crossings (Easwarapadcham et al., 2013; Liu et al., 2010). Pedestrian delay can be used as a metric to compare alternative designs at an intersection and signal timing plans at signaled intersections, prioritize projects that aim to reduce vehicle miles within a lane or area, and perform scenario evaluations to determine potential time savings from building a network of separate mixed-use lanes. In addition, delay is one of the main indicators for determining the level of service (Semler et al., 2016).

Analyzing unsignalized crossings is a complex task that involves the intersection of sidewalk flows, pedestrian crossing of a street, and pedestrian judgment over an acceptable gap. Delay at unsignalized intersections refers to the amount of time pedestrians require to obtain a traffic gap that allows them to cross safely. The likelihood of a driver yielding the right of way to a pedestrian in the crosswalk and the volume of traffic are two factors that influence gap availability (NTMP, 2012). One approach to evaluating pedestrian delays is to estimate the number of gaps that are large enough for safe crossings. The method for estimating delay at unmarked intersections is illustrated in Equation 4.6 (HCM, 2000).

$$d_p = \frac{1}{v}\left(e^{vt_G} - vt_G - 1\right) \tag{4.6}$$

Where,

d_p = average pedestrian delay (s),

v = vehicular flow rate (veh/s), and

t_G = group critical gap (s).

At roundabouts, research is limited to date due to the right of way that pedestrians have at crossings, which varies from country to country.

4.3.2 Circulation area

The circulation area is an important measure for evaluating intersection performance in terms of its service to pedestrians. The circulation area consists of two parts: the corner circulation area (used to assess the area designated for pedestrians waiting at the corner) and the crosswalk circulation area (used to assess the area available for pedestrians crossing in the crosswalk). A larger circulation area is considered more favorable from a pedestrian's viewpoint as it provides ample space for pedestrian movements. Table 4.2 show the qualitative description of pedestrian space (HCM, 2010b).

Table 4.2: Qualitative description of pedestrian space.

Pedestrian Space (ft^2/p)	Description
> 60	Ability to move in desired path, no need to alter movements
> 40-60	Occasional need to adjust path to avoid conflicts
> 24-40	Frequent need to adjust path to avoid conflicts
> 15-24	Speed and ability to pass slower pedestrians restricted
> 8-15	Speed restricted, very limited ability to pass slower pedestrians
≤ 8	Speed severely restricted frequent contact with other users

Source: Highway Capacity Manual, (HCM 2010), Transportation Research Board, 2010

4.3.3 Level of service (LOS)

In the field of traffic engineering, the concept of level of service pertains to a metric used to assess the degree to which a traffic system meets the satisfaction of its users concerning factors such as speed, density, delay, congestion, and other relevant criteria. Specifically, in evaluating the quality of pedestrian facilities, the estimation of pedestrian level of service (PLOS) is commonly employed. The process of PLOS estimation is more intricate compared to general level of service evaluations, as it takes into account not only the operational conditions of pedestrian facilities but also the level of comfort and convenience experienced by pedestrians while utilizing these facilities (Singh & Jain, 2011).

Numerous researchers have conducted various studies to develop pedestrian level of service (PLOS) for different types of facilities, considering several factors such as flow rate, delay, unit area, speed, surrounding land use, restriction, volume, safety, surface, and width. The Highway Capacity Manual defines PLOS as a measure of user satisfaction with the quality of pedestrian facilities, which can be determined using the PLOS score or delay, depending on the type of intersection. For signalized intersections, the PLOS score is computed based on multiple parameters, including the crosswalk adjustment factor, the vehicle volume adjustment factor, the vehicle speed adjustment factor, and the pedestrian delay factor (NTMP, 2012). In contrast, at unsignalized intersections, the delay is the sole factor that determines the PLOS. Table 4.3 illustrates the pedestrian level of service at intersections (HCM, 2010b). PLOS estimation is a crucial tool in understanding and enhancing pedestrian experiences at intersections, ultimately contributing to safer and more efficient pedestrian facilities.

Table 4.3: Pedestrian level of service (PLOS) at intersections.

LOS Measure	Intersection Type		
	Signalized Intersection LOS score	**Unsignalized Intersection Delay (s)**	**Roundabout Delay (s)**
A	≤ 2.00	0-5	0-5
B	> 2.00-2.75	5-10	5-10
C	> 2.75-3.50	10-20	10-20
D	> 3.50-4.25	20-30	20-30
E	> 4.25-5.00	30-45	30-45
F	> 5.00	> 45	> 45

Source: Highway Capacity Manual, (HCM 2010), Transportation Research Board, 2010

In a series of diverse studies, researchers have investigated pedestrian behavior and factors influencing pedestrian level of service (PLOS) in various contexts. A qualitative study in Bangladesh emphasized the significance of comfort and safety as pivotal factors impacting pedestrian crossing behavior (Kumar Saha et al., 2013). In India, Nagraj and Vedagiri (2013) developed a PLOS model through a qualitative survey technique incorporating vehicle turning patterns, traffic flow, and pedestrian crossing frequencies every 15 minutes. Marisamynathan and Vedagiri (2017) focused on deriving essential parameters, such as pedestrian delay, traffic volume, and the probability of pedestrian-vehicle interaction at signaled crosswalks, to formulate a comprehensive level of service model. Bian et al. (2009), in their study on signaled intersections, identified key variables influencing PLOS, including vehicle right turns and bike sizes in relation to pedestrian lanes during pedestrian green time, as well as tolerant vehicles turning left and bikes approaching pedestrian lanes, considering bike size, alongside pedestrian delays on the street parallel to the pedestrian walkway. These studies contribute valuable insights into enhancing pedestrian safety and convenience at intersections, thereby promoting pedestrian-friendly environments in urban areas.

4.4 Performance Evaluation by Simulation

The rapid growth of technological applications and the imperative for the availability of techniques to make quick and accurate decisions in the future have led to the development of the philosophy of simulation. Traffic simulation is a process that replicates real-world conditions in a virtual environment. This approach is beneficial as it enables the identification of potential problems, the exploration of possible solutions, and the development of plans without the need for costly physical implementation.

However, simulation requires significant expertise in model creation, and results cannot always be relied upon as estimations may be used to generate data, which may cause erroneous results. The simulation process goes through four main stages: collecting and analyzing data, creating and calibrating the model, creating different scenarios, and finally analyzing the results (OCAKDAN, 2010).

The VISSIM simulation program, developed by the German company Planung Transport Verkehr AG (PTV), is considered as one of the premier microscopic simulation software available for modeling multimodal transport operations. It provides an ideal environment for testing and evaluating different traffic scenarios in a highly realistic and detailed way before final implementation (PTV Group, 2018). VISSIM has the ability to control vehicle and driver attributes and model the interaction between vehicles in both lateral and longitudinal positions. Moreover, it uses "conflict areas" to represent gap-seeking behavior where the traffic flow of a vehicle or pedestrian should give priority and search for gaps in other traffic (vehicle or pedestrian) flows. These advanced features make it one of the most preferred software for modeling the behavior of vehicles and pedestrians at intersections (Sindi, 2011).

Recently, VISWALK was developed as an addition to VISSIM with the goal of simulating and analyzing pedestrian flows in a more realistic way than what is possible by only using VISSIM. The VISWALK tool can be used within VISSIM or separately as an external program. With this tool, it becomes possible to simulate both pure pedestrian flows and the dynamic interactions between pedestrians and vehicles (Friis and Svensson, 2013). Furthermore, VISSIM can produce various metrics of efficacy and performance, such as total delay, travel time, number of stops, LOS, and queue lengths for all default travel modes or user input, including pedestrians and bicycles (Ishaque and Noland, 2007).

To simulate pedestrians, two VISSIM models can be used: the Helbing model (Social Force Model) and the Weidermann model. In the Social Force Model (Helbing, 2001), the software is able to consider pedestrian behavior when walking into areas, which is dictated by the availability of pre-designed or estimated obstacles and routes. When considering the Weidermann model, pedestrians are treated as vehicles and exist only in order to provoke a conflict with real vehicular traffic (PTV Group, 2018). In complex and irrational pedestrian scenarios and large flows, the Helbing method is recommended due to its capability to present the case in a more reliable way (Friis and Svensson, 2013).

Numerous studies have been conducted by researchers using VISSIM to simulate the traffic of vehicles and pedestrians at intersections in order to evaluate and improve efficiency based on various performance measures. Duran (2010) utilized the VISSIM microsimulation model to investigate the effect of pedestrian volume and crossing location on intersection entry capacity. Four different pedestrian volumes and crossing locations were examined in the morning and afternoon peak hours. The simulation model's output was validated using the HCM 2010 model, and an analysis of the findings revealed an overwhelming concurrence between the two models, demonstrating the suitability of using VISSIM software to simulate traffic at intersections. Similarly, Boenisch and Kretz (2009) conducted a study to simulate the interaction of pedestrians and vehicles at midblock crossings on a two-way road, focusing on the "conflict areas" and assuming that vehicles have the right of way over pedestrians. Contrary to expectations, the study showed that vehicles experienced delays, despite the pedestrians giving priority to the vehicles. The study also noted that pedestrians sometimes accepted the headway, even if it was insufficient to allow them to cross the street without causing the vehicles to slow down or stop.

Esmer (2021) conducted a study to investigate the impact of changes in pedestrian volume on intersection capacity in the case of an unsignalized roundabout, a signalized roundabout, and a four-way signalized intersection. Results were compared based on measures of average speed, average delay, average number of stops, emissions, and fuel consumption. In another study, Song et al. (2017) investigated the impact of phase sequence and pedestrian crossing patterns on the traffic flow of vehicles and pedestrians at a signalized intersection. The study aimed to evaluate the performance of different scenarios by analyzing measures such as travel time, delay, and traffic volume for both vehicles and pedestrians. Oskarbski et al. (2016) conducted a study on intersection analysis in the context of pedestrian traffic with the objective of improving traffic conditions and pedestrian safety at signaled intersections. The study proposed two main options: complete separation of pedestrian and vehicular traffic at the pedestrian crosswalk and eliminating collisions caused by vehicles leaving the intersection using a conditional green arrow signal to turn right. Metrics such as vehicle and pedestrian green time, travel time, and pedestrian delay were utilized to evaluate the proposed solutions.

The average waiting time and pattern of arrival and departure of pedestrians were the indicators addressed by Suh et al. (2013) in their study that focused on the observed pedestrian behavior at the crosswalk, taking into account the interaction of pedestrians and vehicles in a microscopic simulation environment. It was seen that pedestrian behavior was strongly related to the cross-street traffic queue clearance time and subsequent traffic flow, not the pedestrian signal indication. Jauregui et al. (2020) sought to improve intersection performance measures, including pedestrian crossing time and level of service, and reduce vehicle queue length by redesigning the geometry of refuge islands and implementing full signal control with pedestrian detection sensors. In a similar vein, Gupta and Patel (2014) conducted simulations at a congested urban intersection where vehicle-pedestrian conflicts were prevalent. They utilized pedestrian delay as a metric to compare the simulation results against field observations, with the objective of identifying appropriate solutions to mitigate delays and improve pedestrian safety.

Greger and Wred, (2019) concluded in their study, which focused on the delay of pedestrians at midblock crossings, that reducing the cycle time had a positive effect on reducing pedestrian delay. Yulianto and Putri (2021) used the delays of pedestrians and vehicles to compare the performance of the demand-responsive Pelican crossing at the midblock pedestrian crossing facility with the normal Pelican crossing. Additionally, Fi and Kovács Igazvölgyi (2014) investigated the effect of different geometric designs (with and without refuge islands) and various volumes of pedestrians and vehicles on the delay and level of service for both pedestrians and vehicles at midblock crossings. Their findings shed light on the importance of considering pedestrian delay and level of service for different geometric designs when planning and designing midblock crossings.

The previous studies collectively contributed valuable insights into the intricate dynamics of pedestrian behavior and the means to optimize intersection performance in the presence of pedestrian and vehicle interactions. The current study employed an interactive modeling approach utilizing the VISSIM program to analyze and assess performance of four consecutive intersections located in a bustling shopping district in Sakarya city. The evaluation focused on crucial metrics, including delay, level of service, speed, number of stops, queuing, emissions, and fuel consumption, with a specific emphasis on pedestrian-related traffic outputs, encompassing delay, level of service, speed, and number of stops. The principal aim of this research was to offer a comprehensive quantitative analysis of the selected intersections, considering diverse traffic scenarios, with particular attention to pedestrian traffic aspects. Through this assessment, the study aimed to gain valuable insights into the functionality and efficiency of the intersections, especially concerning pedestrian movement and safety.

CHAPTER 5. METHODOLOGY

5.1 Study Area

Turkey has sought in recent years, through the Healthy Cities Association, which was established in 2005, to intensify efforts to give priority to pedestrians in traffic, as important regulations have been set by municipalities for pedestrians, opening certain areas of the city for pedestrian use only, and increasing the number of signs that mention that pedestrians take priority in traffic. Sakarya City serves as one of the communities that has sought to reinforce these efforts to encourage walking and reduce reliance on vehicles. According to the most recent General Directorate of Population and Nationality Affairs data, the population in Sakarya reached 1,080,080 people, and the Serdivan district, where the study area resides, represented the second most populous district in the city.

Figure 5.1 : The location of the four selected intersections.

The study was conducted in the central business district of Serdivan, which contains shopping malls, hotels, restaurants, schools, mosques, a municipal building, and the Academy of Arts, which contributes to making it a pedestrian attraction as well as having high vehicular traffic due to its location between the city center and the university. Four main intersections were selected, as shown in Figure 5.1. Three of them are roundabouts, and the fourth is a normal, uncontrolled intersection. The Municipal Roundabout and Sapak Roundabout connect four major streets: Çark Street, Bağlar Street, Mehmet Akif Ersoy Street, and Şht. Mehmet Karabaşoğlu Street. These intersections are located near the recently opened Mall 54, as well as the Serdivan Municipal Building and Zubeyde Hanım School, which makes pedestrian activity in them constantly increasing. The Serdivan Roundabout, on the other hand, is located near Serdivan Mall and connects Mehmet Akif Ersoy Street and Eski Kazım Paşa Street. Finally, the Vatan intersection is located near a residential neighborhood and along Çark Street, which is crowded with small local shops.

5.2 Data collection

Various techniques can be utilized for collecting traffic data, including on-site measurements using pen and paper, hand-held click counters, and video recording. Video recording is more useful due to its efficiency, high accuracy, and limited requirements for human resources throughout the data gathering process.

The first procedure was to determine certain angles at the intersection and set the camera at a certain height to be able to clearly see all the approaching legs of the intersection and sidewalks and easily monitor the pedestrian and vehicle traffic. Three days during the weekdays and one day at the weekend were chosen to collect data, with a total of 14 hours for each intersection. The times of the video recordings were set during the peak times of the day, between 7:00 AM and 9:00 AM in the morning peak time when people were going out to work and between 4:00 PM and 5:00 PM in the evening peak time when they were returning from work. On weekends, the time was set between 13:00 and 15:00 when people went out for shopping and leisure activities.

The approaching legs of the intersections were named as shown in Figure 5.2 to count vehicles and pedestrians separately. Parameters recorded in the field included vehicle volumes, pedestrian volumes, and vehicle type. Vehicles are categorized by type into cars, trucks, buses, minibuses, and motorcycles.

During the extraction of vehicle data, the morning rush hour and the evening rush hour were separately determined, and the average was taken for the three days of the week for each peak hour, and the same was done for pedestrians by taking the average of three days. Initial evaluation of the collected data revealed that the data obtained during the weekend and evening peak hours presented similar volume and traffic count parameters. These two are significantly different from the morning peak hours. Thus, weekend data were neglected, and only evening data was used in the simulation model to eliminate the repetition of the analysis.

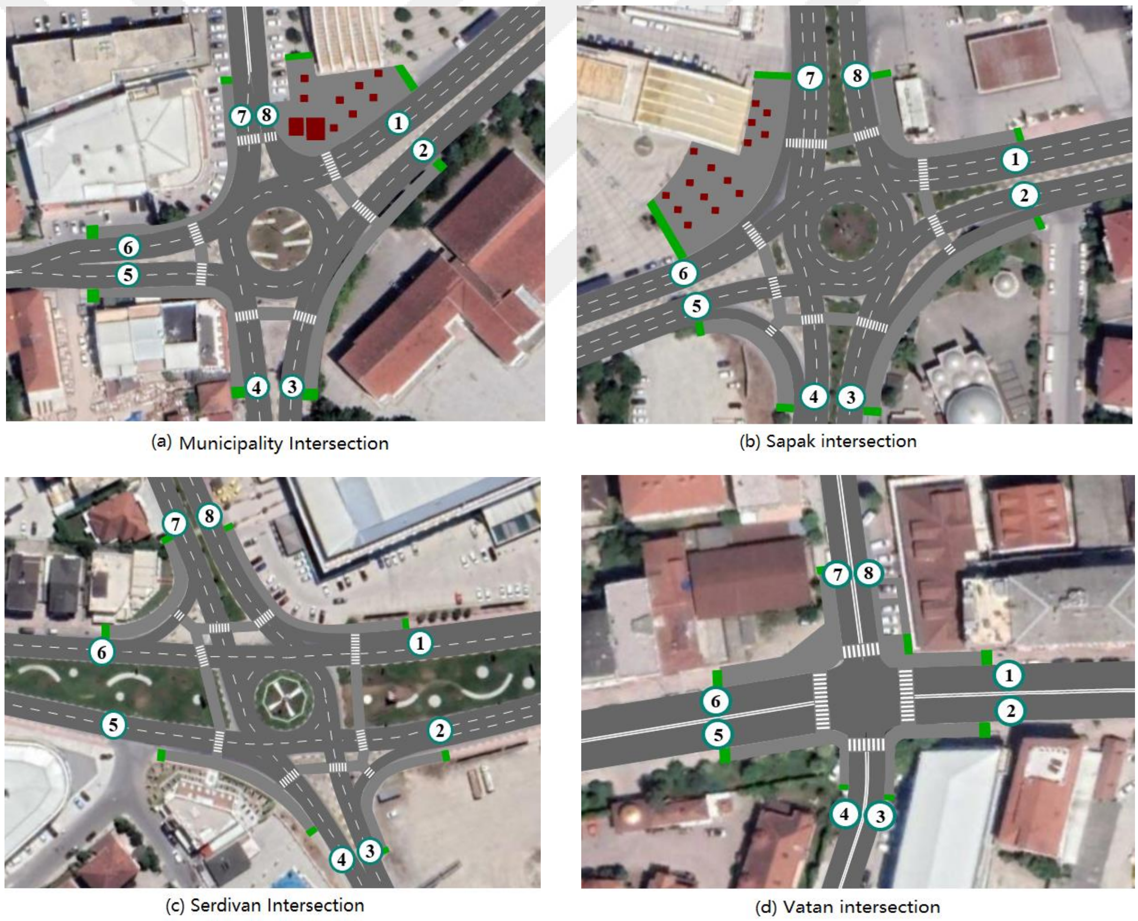

Figure 5.2 : Intersections approaching legs.

Table 5.1,Table 5.2, and Table 5.3 show a comprehensive summary of counted vehicular and pedestrian traffic at Vatan Intersection. The count results for the other intersections are presented in Appendix A. The data presented in these tables form a fundamental basis for the subsequent analysis and evaluation of intersection performance.

Table 5.1 : Vehicle flow during the morning peak hour at Vatan intersection.

Type of vehicle	**1→8**	**1→6**	**1→4**	**3→2**	**3→8**	**3→6**	**5→4**	**5→2**	**5→8**	**7→6**	**7→4**	**7→2**
Motorbike	3	9	1	0	1	1	1	11	1	3	2	4
Bus	4	13	1	0	0	0	1	13	1	2	1	3
Truck	1	8	1	0	1	1	1	6	1	2	0	1
Car	29	204	4	4	19	12	18	342	32	64	19	32
Minibus	7	88	0	0	1	1	1	104	10	20	4	6
Total	44	322	7	4	23	15	22	476	45	91	26	46
		373			42			543			163	

Table 5.2 : Vehicle flow during the evening peak hour at Vatan intersection.

Type of vehicle	**1→8**	**1→6**	**1→4**	**3→2**	**3→8**	**3→6**	**5→4**	**5→2**	**5→8**	**7→6**	**7→4**	**7→2**
Motorbike	8	33	2	1	3	1	2	30	10	7	4	7
Bus	3	10	1	0	0	0	0	15	4	0	0	2
Truck	1	9	0	1	1	1	2	13	3	1	1	2
Car	98	499	19	7	40	24	25	445	84	148	59	111
Minibus	10	89	1	0	4	3	4	114	8	12	5	4
Total	120	640	23	9	48	29	33	617	109	168	69	126
		783			86			759			363	

Table 5.3 : Pedestrian flow during the morning and evening peak hour at Vatan intersection.

	Morning									**Evening**								
No. of lane	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Total**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Total**
1	0	1	1	0	0	26	1	11	40	0	2	1	0	0	58	3	14	78
2	0	0	2	0	19	2	1	4	28	1	0	5	1	32	2	0	7	48
3	2	1	0	0	1	0	0	3	7	2	8	0	0	1	0	0	8	19
4	1	1	0	0	3	2	2	2	11	0	3	0	0	5	5	4	0	17
5	0	19	1	5	0	5	7	1	38	0	40	0	5	0	3	14	1	62
6	17	2	0	2	1	0	4	3	29	76	3	0	1	1	0	1	1	83
7	1	1	0	2	6	3	0	1	14	2	3	0	15	16	1	0	0	37
8	10	6	2	0	0	2	0	0	20	25	11	5	0	0	1	0	0	42

5.3 Traffic Simulation Modeling

The simulation modeling process was done using VISSIM 2022 software. To ensure reliable results, special attention was given to various geometric aspects, such as the method of connecting approach legs to the intersection and the precise placement of pedestrian crosswalks. Additionally, factors influencing speeds and other observable effects were meticulously accounted for to maintain consistency and validity throughout the simulation. It is important to note that all figures presented in this section and the subsequent section are based on data from the Vatan Intersection, chosen as an illustrative example for the four studied intersections.

5.3.1 Links and areas

During the model setup, the initial phase involved the creation of links within the VISSIM software. Geometric parameters, including lane width, island diameter, approach lane width at island joining points, the width and location of pedestrian crossings, as well as sidewalk areas, were carefully measured using data from Google Earth. The behavior for vehicle links was selected as "urban motorized" while for pedestrian crosswalks, the attribute was selected as "pedestrian area". The rest of the paths for pedestrians were drawn from the network object as "Area" . Upon completing the drawing process for the links and areas, the field data set was meticulously entered and coded in the VISSIM model. The model incorporated volumes of vehicles and pedestrians, along with their respective routes, aiming to provide a realistic representation by maintaining the proportions of different vehicle types based on actual field data. For pedestrians, a comparable proportion of men and women were included, which is as identical to reality as is feasible.

Figure 5.3 and Figure 5.4 illustrate the traffic volumes recorded for vehicles and pedestrians during the morning rush hour at Vatan Intersection, offering a comprehensive view of the intersection's activity during the peak period. Moreover, Figure 5.5 and Figure 5.6 offer a detailed depiction of the various routes taken by vehicles and pedestrians within the intersection. These illustrations shed light on the intricate interactions and movements that occur, highlighting the complexity of traffic patterns and pedestrian behavior at the intersection.

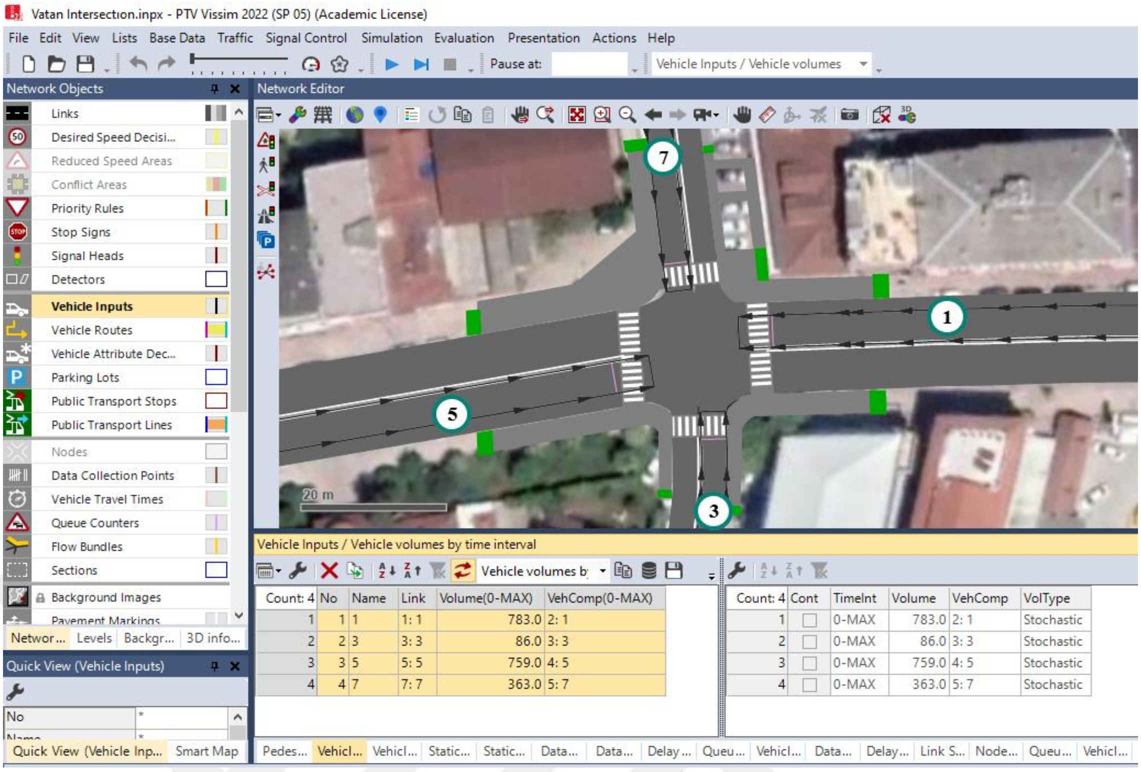

Figure 5.3 : Vehicle volumes in the morning peak hour at Vatan intersection.

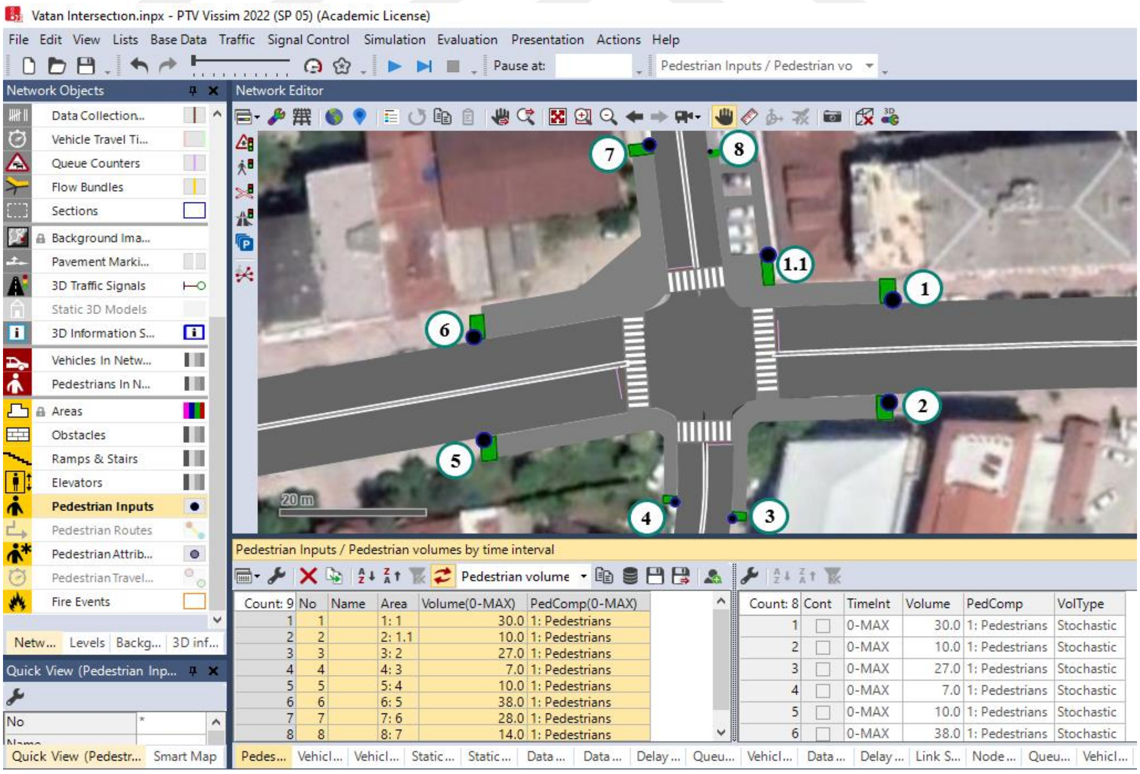

Figure 5.4 : Pedestrian volumes in the morning peak hour at Vatan intersection.

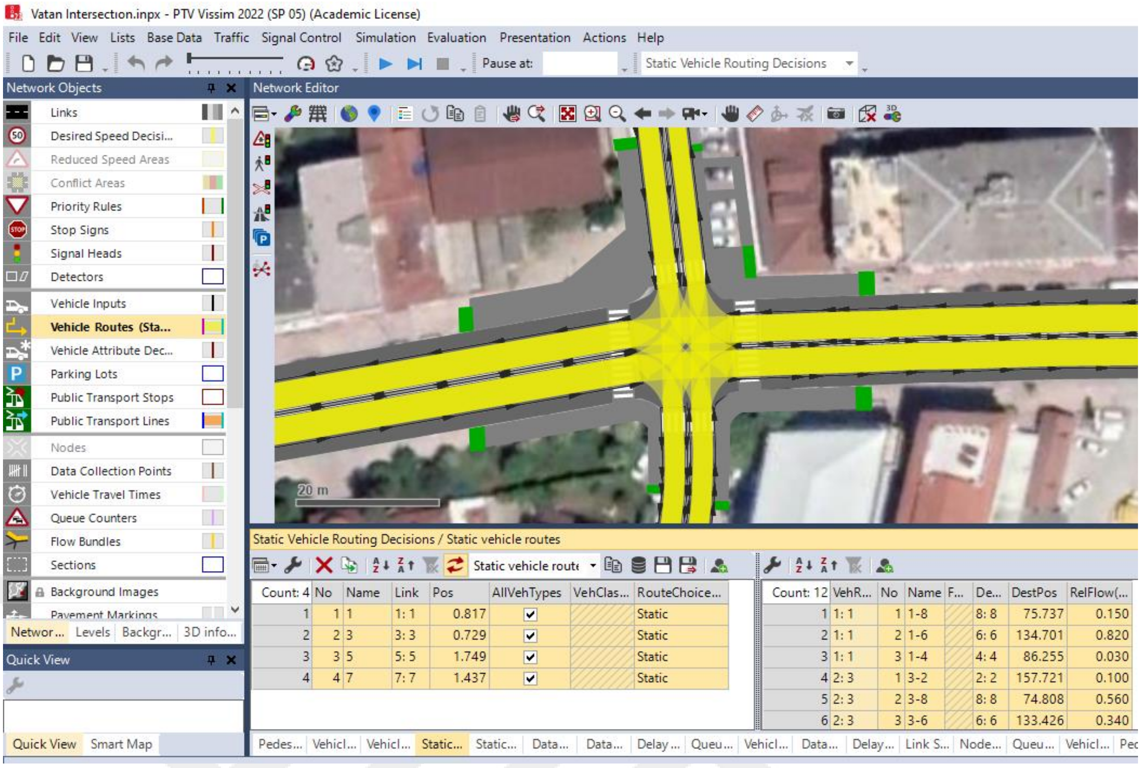

Figure 5.5 : Vehicle routes at Vatan intersection.

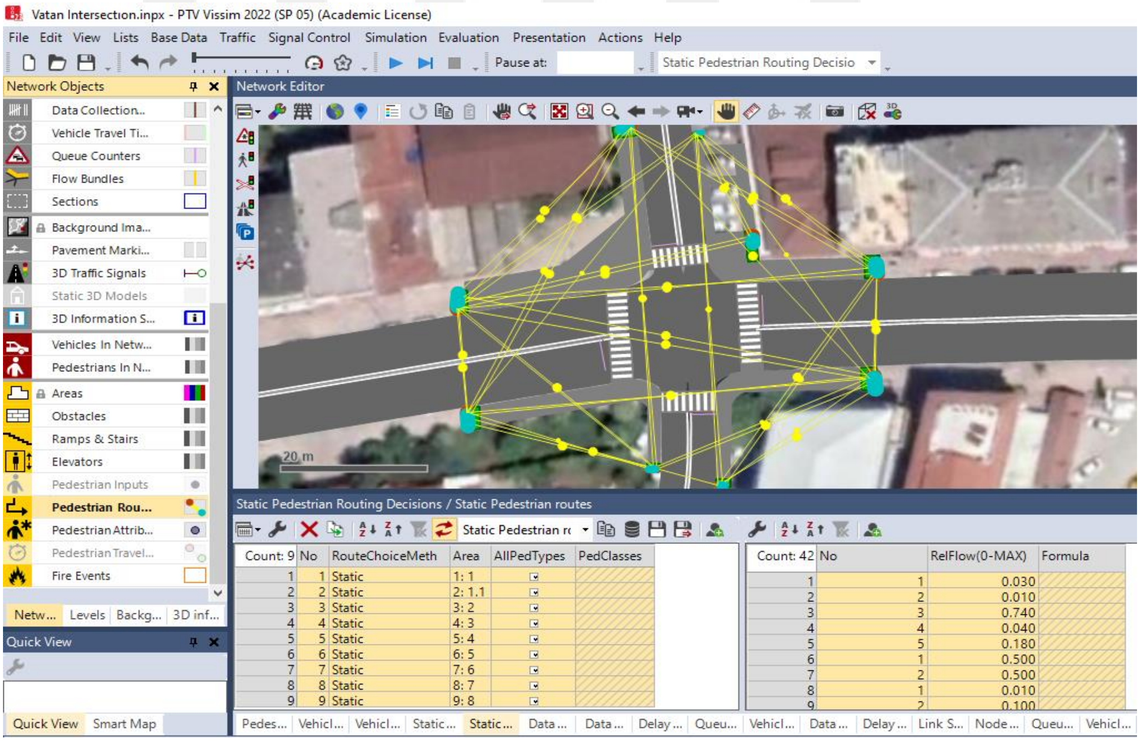

Figure 5.6 : Pedestrian routes at Vatan intersection.

5.3.2 Speed and reduced speed areas

The vehicle speed has been set at 50 km/h according to the vehicle speed in urban streets recommended by the General Directorate of Highways of Turkey.

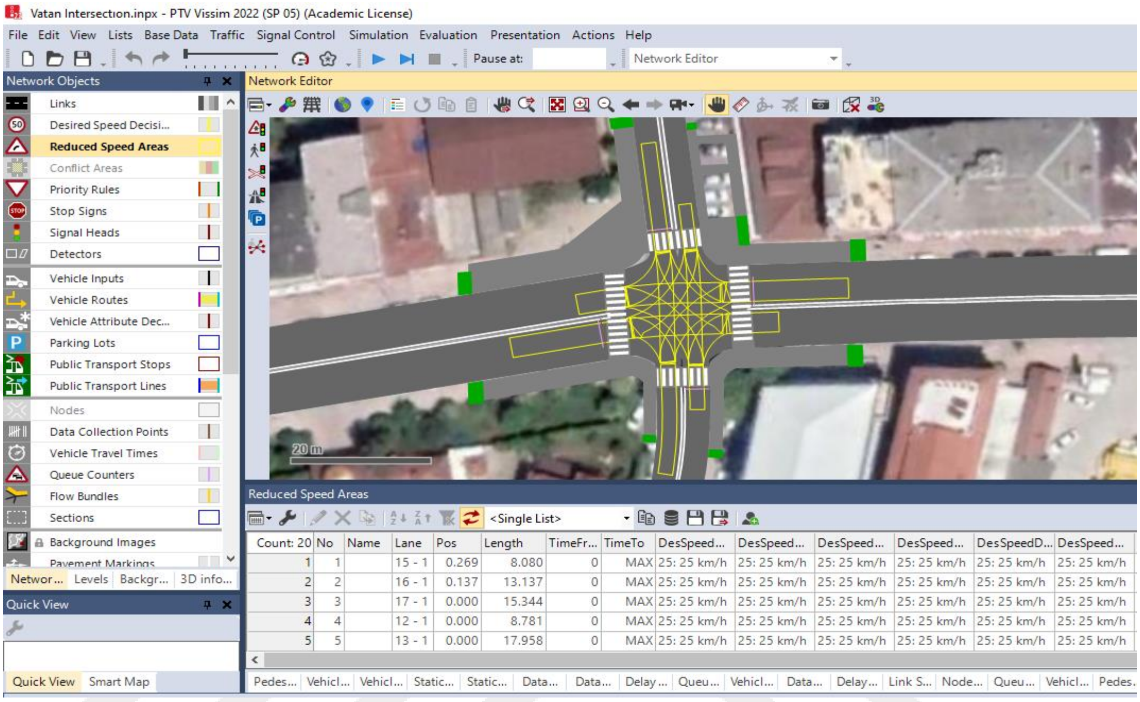

Figure 5.7 : Reduced speed areas at Vatan intersection.

Reduced speed areas have been added inside the intersection and in the approach arms 15 meters from the pedestrian crossing before entering the intersection, forcing vehicles to start slowing their speeds to 25 km/h compared to the rest of the motorized link, which seems reasonable and close to reality. Figure 5.7 shows the reduced speed areas at Vatan Intersection. On the other hand, the desired speed of pedestrians was determined, based on the literature and field observations, at 1.12 m/s for males and 0.95 m/s for females.

5.3.3 Conflict areas and priority rules

The interaction zones occur when two or more road users approach each other. The vehicle-vehicle interaction zones are modeled as "conflict areas" with the default values in VISSIM. In the case of vehicle-pedestrian interaction zones, the modeling was conducted using two separate approaches. The first represents the typical case, where "conflict area" was used with the default values in VISSIM, assuming that vehicles give full priority to pedestrians approaching the crosswalks. Figure 5.8 shows vehicle-vehicle and vehicle-pedestrian conflict areas at the Vatan Intersection.

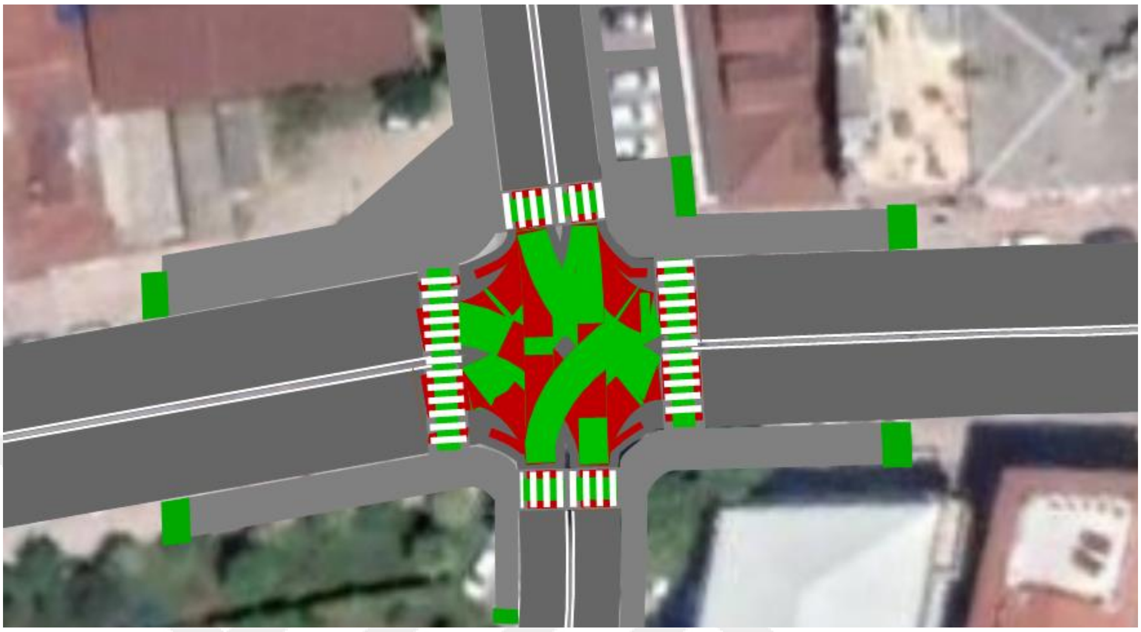

Figure 5.8 : Conflict areas at Vatan intersection.

In the second case, the local situation was simulated as much as possible. When collecting field data, it was observed that most drivers do not comply with giving priority to pedestrians and stop only when the pedestrians have entered the crosswalks, which in turn forces pedestrians to stop and wait for the appropriate gap in the vehicles' flow. To model the behavior of pedestrians in choosing the gap, the "priority rule" was applied. The proper gap to cross may vary depending on the person and the location, in this case, the gap has been assessed based on field observations to be 3 seconds, and the rest of the parameters have been set to default values in VISSIM. This method was applied just to the Vatan intersection as a model for comparison between the local and typical conditions. The rules that govern pedestrian traffic from waiting area one (W1) to waiting area two (W2) are illustrated in Figure 5.9. Pedestrians are presumptively designed to yield to vehicles in lane 1 that are within a time headway of 3 seconds of the crosswalks. Therefore, if a vehicle is in the zone marked by the arrow, no pedestrian in the waiting area will cross the curb line. Figure 5.10 displays pedestrians waiting for a suitable gap before crossing the road. The vehicle characteristics, encompassing attributes such as acceleration, deceleration, torque, and other pertinent parameters, were established with their default values as provided by the VISSIM simulation program. Similarly, the driving and walking behaviors of the vehicles and pedestrians within the simulation environment were also defined using the default settings provided by the VISSIM software.

Figure 5.9 : Priority rule explanation for gap-seeking pedestrians.

Figure 5.10 : The pedestrian stopped for seeking a gap.

5.4 Traffic Simulation Analysis

The four intersections were analyzed separately. The typical case was simulated at the Municipality, Sapak, and Serdivan intersections, where the modeling procedure was carried out utilizing "conflict areas" assuming that vehicles give full priority to pedestrians. The analysis was performed by creating five different scenarios in addition to the current intersection vehicle and pedestrian movements by increasing pedestrian volumes by 200%, 400%, 600%, 800%, and 1000% while keeping the vehicle volumes constant. At the Vatan intersection, two situations were conducted for simulation: the typical and the local cases. In the local case, the priority rule was implemented, assuming that pedestrians wait for a suitable gap in the vehicles' flow to cross the street, where the vehicle stops only when the pedestrian has already entered the pedestrian crosswalks. Four scenarios have been identified for both cases, in addition to the current traffic situation at the intersection. The percentage increases in pedestrian volumes were 200%, 400%, 600%, and 800%. The volume of the vehicles was also kept constant for all scenarios. The purpose of simulating the intersection using two models was to compare the typical and local cases.

The simulation parameters were set to run for 3600 seconds, and the resolution was set to 10 time steps per simulated second to ensure consistency across all scenarios. Critical metrics such as delay, level of service, speed, number of stops, queuing, emissions, and fuel consumption were evaluated during the simulation, as were pedestrian traffic outputs, including delay, level of service, speed, and number of stops. Figure 5.11 shows the vehicular and pedestrian traffic at Vatan Intersection during the analysis process.

Figure 5.11 : The 3D view of Vatan intersection during the simulation process.

CHAPTER 6. RESULTS AND EVALUATION

6.1 Introduction

The evaluation process involved calibrating performance metrics at intersections for both vehicles and pedestrians using VISSIM models. Seven performance measures were calibrated for vehicles, including average delay, level of service, speed, number of stops, queue length, emissions, and fuel consumption. For pedestrians, the calibrated performance measures were average delay, level of service, speed, and number of stops. This chapter presents the findings of the analysis operations in two stages. Firstly, the results for Municipality, Sapak, and Serdivan intersections (MSSI) are presented, assuming the typical case. Secondly, the findings for the Vatan intersection (VI) are presented, considering both the typical and local cases. The location of the arrangement of intersections is given in Figure 5.1.

6.2 Results of Municipality, Sapak and Serdivan Intersections (MSSI)

Table 6.1 shows the volumes of vehicles and pedestrians that enter the three intersections in the current traffic situation, while Figure 6.1 and Figure 6.2 show the change in the volumes of vehicles during the increase in the volumes of pedestrians according to the different scenarios. An analysis of the curves reveals that the change in vehicle volumes during the morning hours was relatively slight, but it was noticeable in the evening, since fewer vehicles were accessing the intersection with a higher pedestrian volume. The results of the performance metrics at the three intersections are shown in Table 6.2 - Table 6.14.

Table 6.1 : The current volumes of vehicles and pedestrians at MSSI.

Type of Traffic	Municipality Intersection		Sapak Intersection		Serdivan Intersection	
	Morning	Evening	Morning	Evening	Morning	Evening
Vehicles	1849	2329	2889	3877	2615	3170
Pedestrians	244	475	108	284	103	300

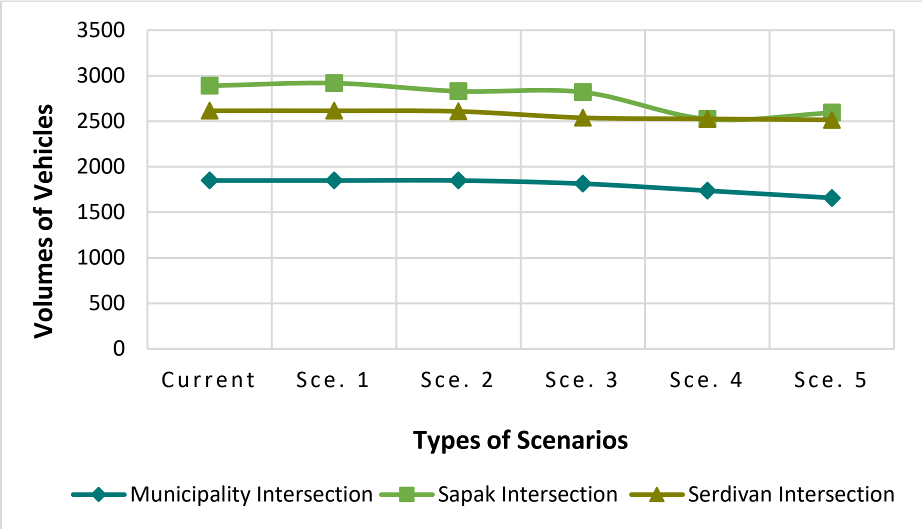

Figure 6.1 : The change in vehicle volumes in the morning at MSSI.

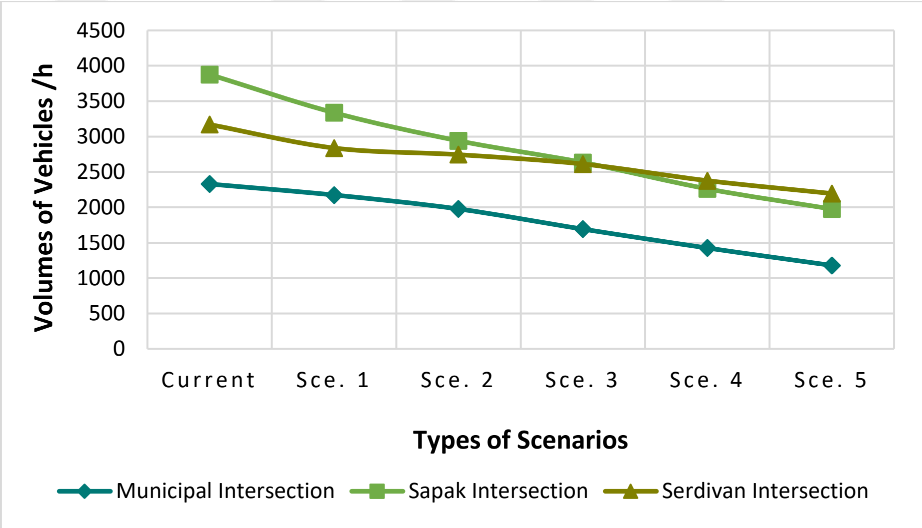

Figure 6.2 : The change in vehicle volumes in the evening at MSSI.

6.2.1 Average delay and LOS

The calculation of delays for both vehicles and pedestrians involves determining the difference between the actual time taken to traverse a route and the theoretical travel time. Based on the delay data, the level of service is calculated. Figure 6-3 - Figure 6.5 illustrate the change in delay and the level of service for vehicles, while Figure 6.6 - Figure 6.8 illustrate the change in delay and the level of service for pedestrians at the MSSI according to the different scenarios.

Table 6.2 : The morning results of the average delay and LOS for vehicles at MSSI

Types of Scenario	Municipality Intersection		Sapak Intersection		Serdivan Intersection	
	Delay (s/veh)	LOS	Delay (s/veh)	LOS	Delay (s/veh)	LOS
Current	10.30	A	126.07	F	91.37	F
Scenario 1	16.40	C	120.36	F	92.60	F
Scenario 2	35.31	D	120.50	F	94.24	F
Scenario 3	59.80	F	118.26	F	95.00	F
Scenario 4	87.68	F	138.94	F	98.73	F
Scenario 5	104.29	F	132.82	F	100.78	F

Table 6.3 : The evening results of the average delay and LOS for vehicles at MSSI.

Type of Scenario	Municipality Intersection		Sapak Intersection		Serdivan Intersection	
	Delay (s/veh)	LOS	Delay (s/veh)	LOS	Delay (s/veh)	LOS
Current	27.58	D	142.86	F	114.04	F
Scenario 1	63.48	F	159.36	F	130.78	F
Scenario 2	141.76	F	174.92	F	143.05	F
Scenario 3	181.95	F	174.42	F	172.30	F
Scenario 4	224.31	F	201.40	F	203.68	F
Scenario 5	290.37	F	248.81	F	230.82	F

Table 6.4 : The morning results of the average delay and LOS for pedestrians at MSSI.

Type of Scenario	Municipality Intersection		Sapak Intersection		Serdivan Intersection	
	Delay (s/ped)	LOS	Delay (s/ped)	LOS	Delay (s/ped)	LOS
Current	0.58	A	0.58	A	0.09	A
Scenario 1	0.94	A	0.91	A	0.11	A
Scenario 2	1.45	A	1.23	A	0.19	A
Scenario 3	1.69	A	1.52	A	0.34	A
Scenario 4	1.87	A	2.31	A	0.43	A
Scenario 5	4.07	A	2.85	A	0.58	A

Table 6.5 : The evening results of the average delay and LOS for pedestrians at MSSI.

Type of Scenario	Municipality Intersection		Sapak Intersection		Serdivan Intersection	
	Delay (s/ped)	LOS	Delay (s/ped)	LOS	Delay (s/ped)	LOS
Current	1.14	A	0.91	A	0.21	A
Scenario 1	1.28	A	1.20	A	0.25	A
Scenario 2	1.83	A	1.28	A	0.38	A
Scenario 3	2.22	A	1.56	A	0.41	A
Scenario 4	3.17	A	1.96	A	0.44	A
Scenario 5	5.00	A	3.33	A	0.97	A

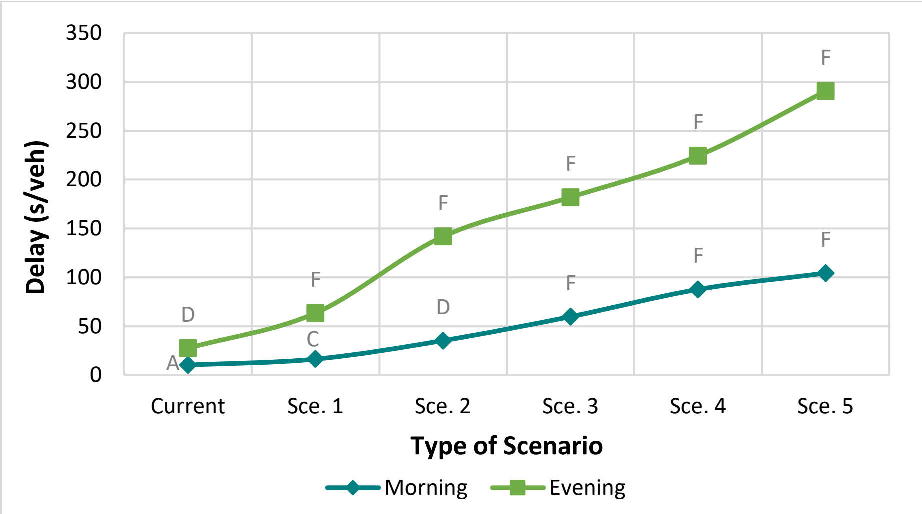

Figure 6-3: The change in delay and LOS of vehicles at Municipality intersection.

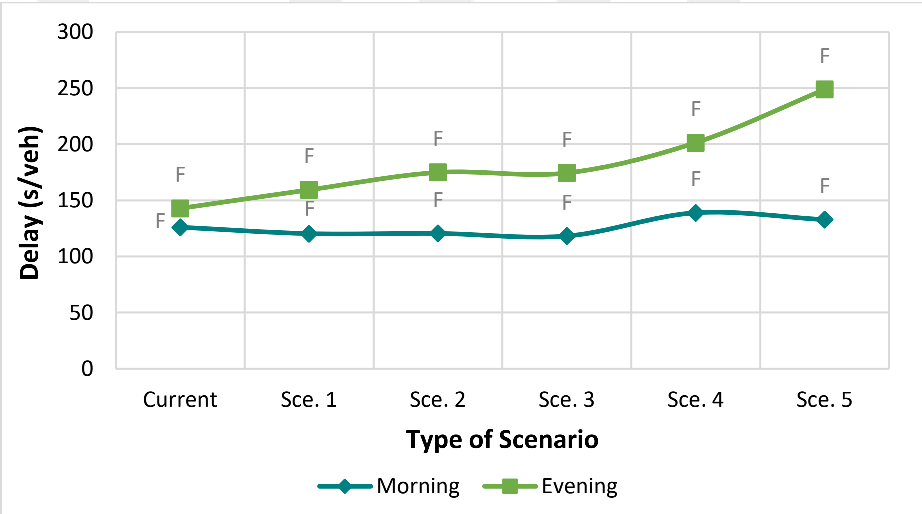

Figure 6.4 : The change in delay and LOS of vehicles at Sapak intersection.

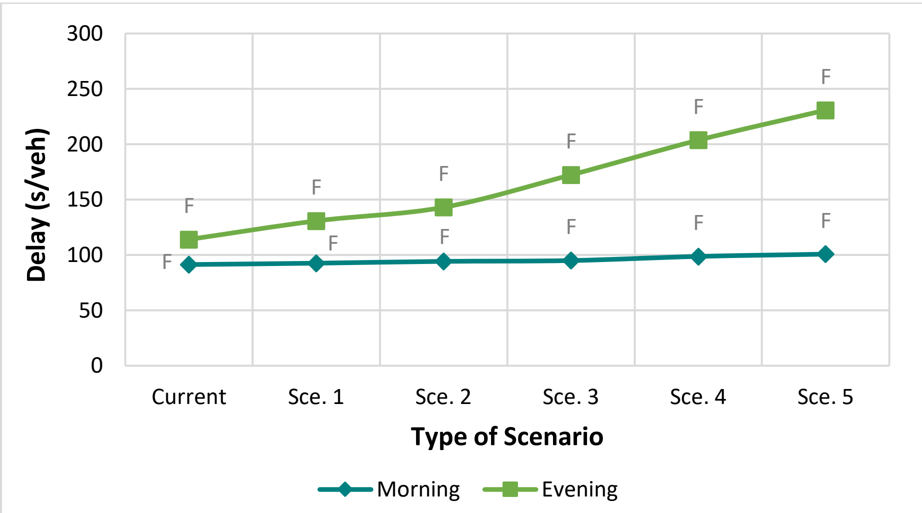

Figure 6.5 : The change in delay and LOS of vehicles at Serdivan intersection.

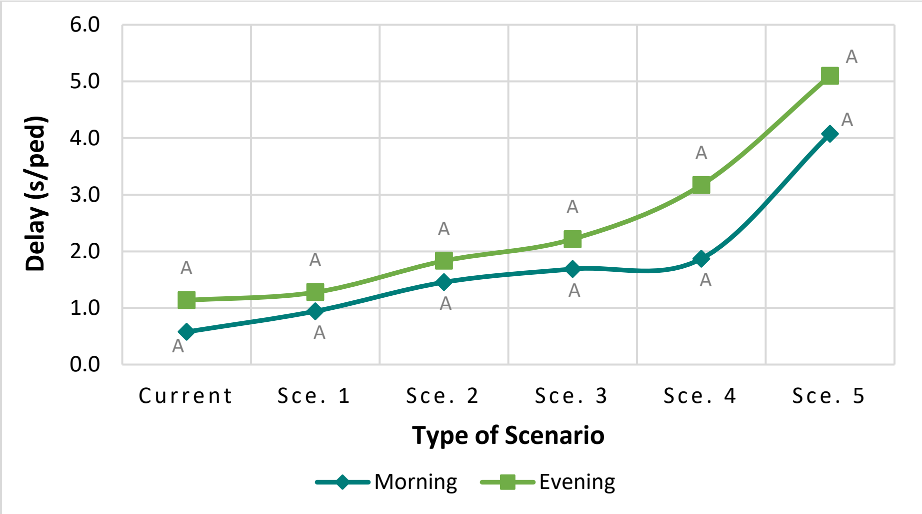

Figure 6.6 : The change in delay and LOS of pedestrians at Municipality intersection.

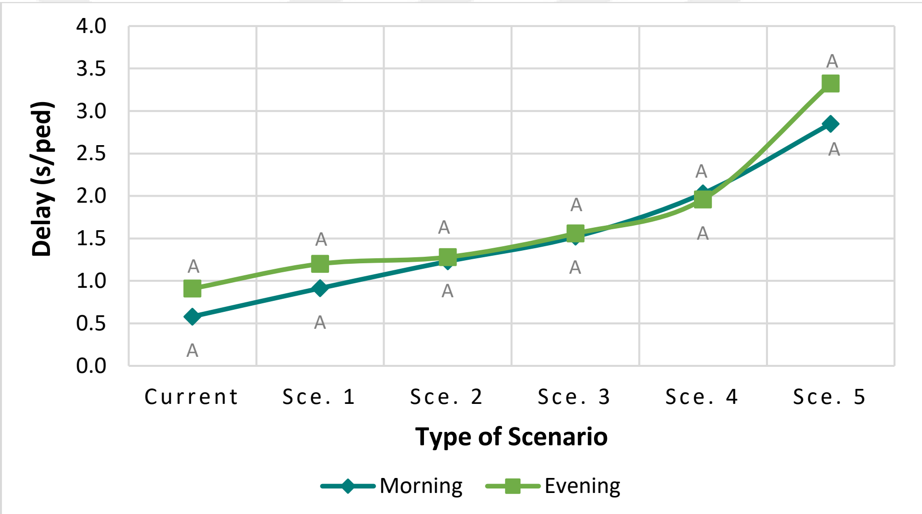

Figure 6.7 : The change in delay and LOS of pedestrians at Sapak intersection

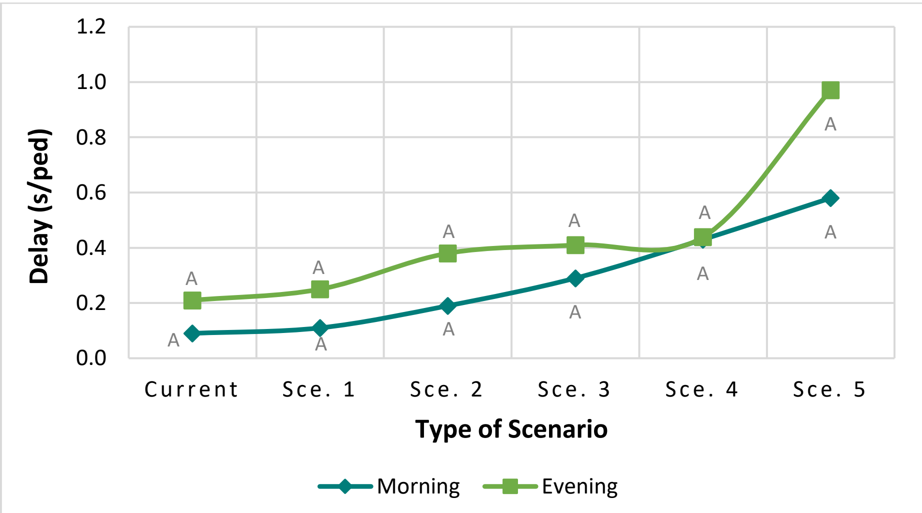

Figure 6.8 : The change in delay and LOS of pedestrians at Serdivan intersection.

Through the graphs showing the change in the delay and the level of service for vehicles at the three intersections, it is clear that the Sapak and Serdivan intersections are currently suffering from increasing delays, which in consequence prompted the level of service to decline to F. With the increase in pedestrian volumes, the delay increases even more, and this increase is noticeable in the evening values compared to the morning values. At the Municipality intersection, the current traffic situation and level of service are at an acceptable level, especially in the morning, but any increase in the volume of pedestrians will lead to an increase in the delay and a decline in the level of service, and this is noticeable after scenario 1. In general, the delay values and level of service after scenario 1 worsen significantly. Comparing the three intersections, the ratio of change in the delay curve at Sapak and Serdivan intersections was less than that of the Municipality intersection, due to the heavy traffic volume of vehicles at these intersections and the low volume of pedestrians, so any increase in the volume of pedestrians would have a slight effect compared to the Municipality intersection, which has fewer vehicles and more pedestrians. For pedestrians, the change in the delay values was very small, and the level of service remained constant at level A despite the increase in the number of pedestrians during the different scenarios. This stability is due to the vehicles' compliance with giving full priority to pedestrians approaching the crosswalks. Since the issue of priority is critical and field observations are mostly different from the theoretical approaches, the issue of priority is studied and discussed in detail at the Vatan Intersection in Section.

6.2.2 Average speed

The average speed of both vehicles and pedestrians is calculated by dividing the total distance covered from the starting point to the destination by the total time taken, encompassing any stops made during the journey. To assess the impact of varying traffic conditions and pedestrian volumes on average speeds, Figure 6.9 - Figure 6.11 display the change in average speed of vehicles, and Figure 6.12 - Figure 6.14 display the change in average speed of pedestrians at the MSSI according to the different scenarios.

Table 6.6 : The results of the average speed for vehicles at MSSI

Scenarios	Municipal Intersection Speed (km/h)		Sapak Intersection Speed (km/h)		Serdivan Intersection Speed (km/h)	
	Morning	Evening	Morning	Evening	Morning	Evening
Current	27.44	17.41	6.22	5.22	11.21	8.86
Scenario 1	22.91	9.90	6.47	5.02	11.03	7.84
Scenario 2	15.11	4.99	6.48	4.73	10.86	7.22
Scenario 3	10.42	3.96	6.59	4.89	10.76	6.06
Scenario 4	7.70	3.21	5.70	4.34	10.41	5.19
Scenario 5	6.65	2.45	5.98	3.59	10.22	4.59

Table 6.7 : The results of the average speed for pedestrians at MSSI.

Scenarios	Municipal Intersection Speed (km/h)		Sapak Intersection Speed (km/h)		Serdivan Intersection Speed (km/h)	
	Morning	Evening	Morning	Evening	Morning	Evening
Current	3.61	3.58	3.55	3.55	3.83	3.80
Scenario 1	3.55	3.54	3.56	3.56	3.80	3.76
Scenario 2	3.52	3.46	3.55	3.51	3.79	3.71
Scenario 3	3.49	3.40	3.54	3.48	3.79	3.66
Scenario 4	3.46	3.32	3.52	3.44	3.77	3.61
Scenario 5	3.37	3.25	3.51	3.39	3.75	3.57

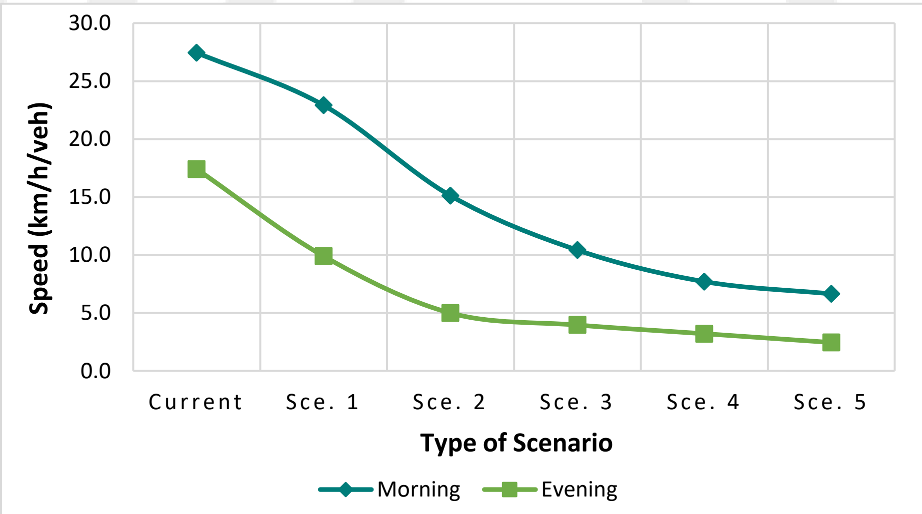

Figure 6.9 : The change in speed of vehicles at Municipality intersection.

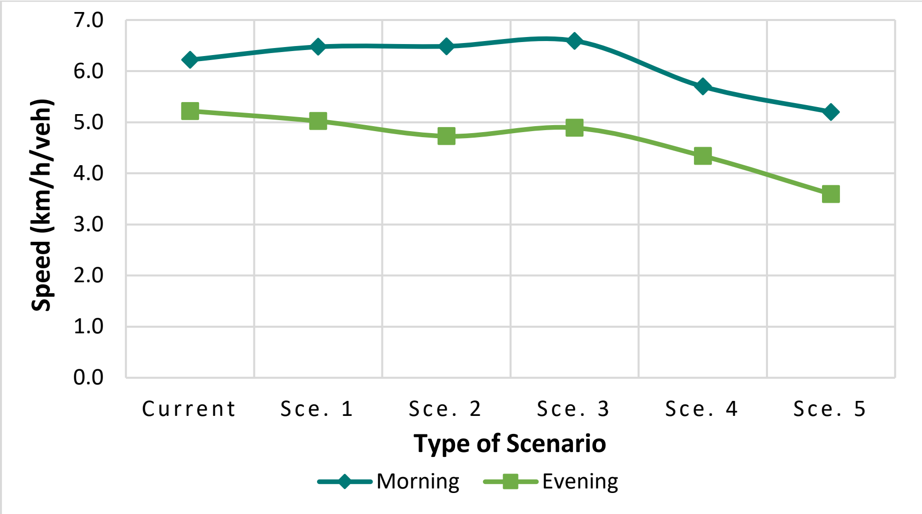

Figure 6.10 : The change in speed of vehicles at Sapak intersection.

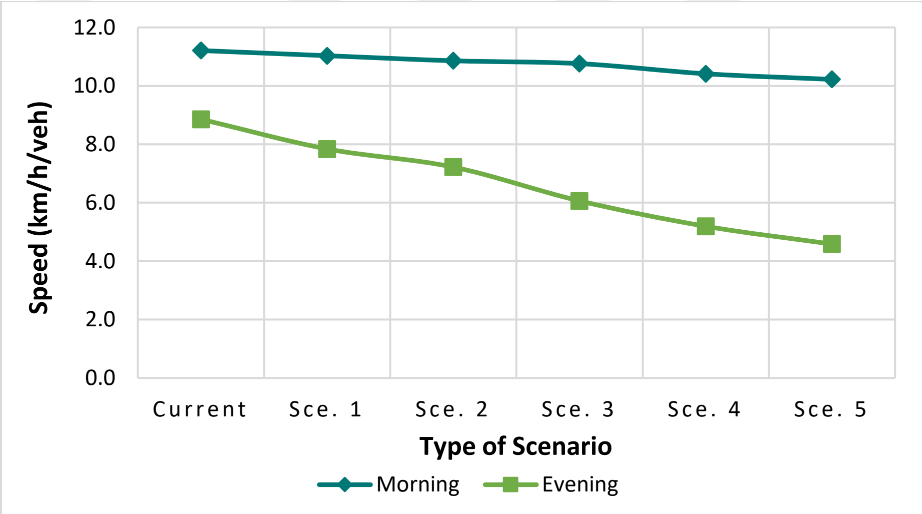

Figure 6.11 : The change in speed of vehicles at Serdivan intersection.

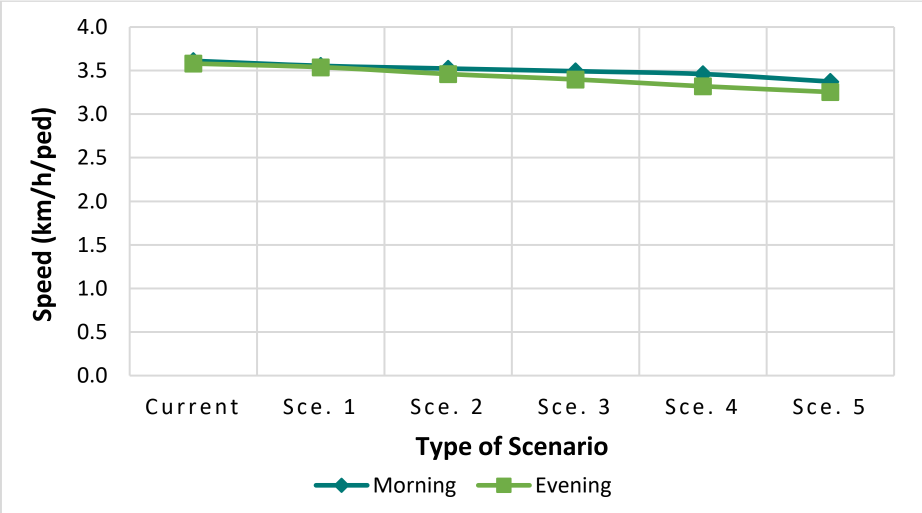

Figure 6.12 : The change in speed of pedestrians at Municipality intersection.

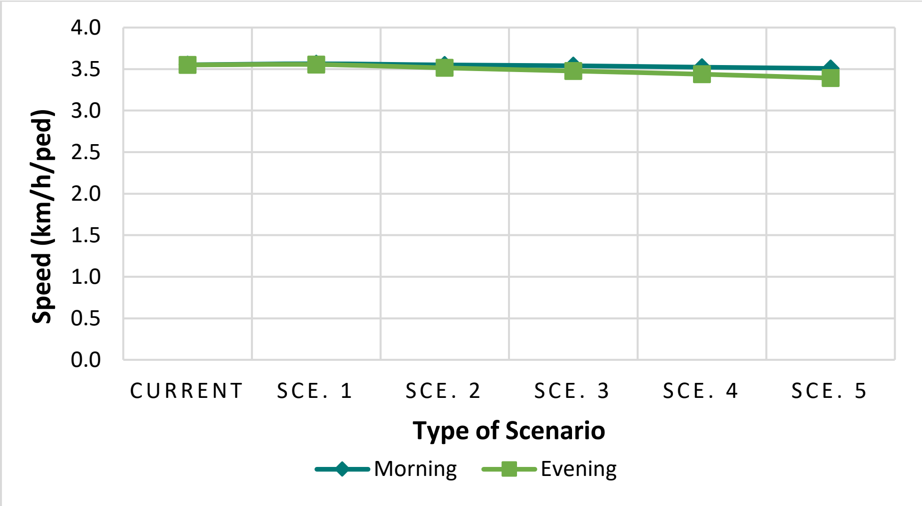

Figure 6.13 : The change in speed of pedestrians at Sapak intersection.

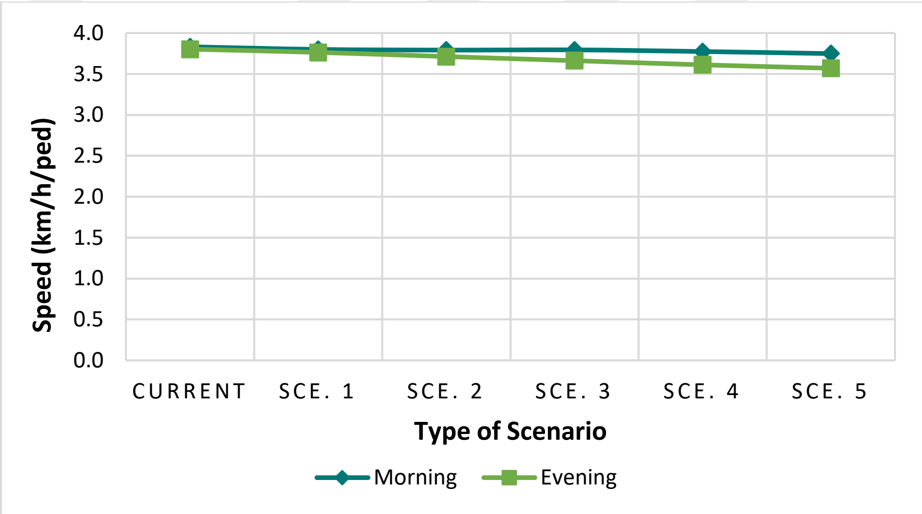

Figure 6.14 : The change in speed of pedestrians at Serdivan intersection.

Based on the illustrations of the average speed of vehicles, the Sapak intersection represents the worst-case scenario among the three intersections, with an average speed value of 6.22 km/h in the morning and 5.22 km/h in the evening, which further drops after scenario 3. At the Serdivan intersection, the average speed was slightly better, with a value of 11.21 km/h in the morning and 8.86 km/h in the evening, which continuously decreases with the increasing pedestrian ratio. The low speed values can be attributed to the high volume of vehicles at these intersections. At the Municipality intersection, the speed values were acceptable in the current situation, especially in the morning, according to the maximum speed limit at the intersection, where the average speed value was 27.44 km/h in the morning and 17.41 km/h in the evening. However, the speed curve sharply drops to low levels as the number of pedestrians increases. Overall, the increase in pedestrian volumes at the intersection of Sapak and Serdivan did not significantly influence the speed of vehicles since the speed of vehicles is actually low at these intersections due to the heavy traffic of vehicles and the low number of pedestrians. In contrast, at the Municipality intersection, the increase in the volume of pedestrians caused vehicles to delay and reduce their speed sharply, as the traffic of vehicles is relatively lower and the pedestrian volume is higher compared to the Sapak and Serdivan intersections, therefore, any increase in the ratio of pedestrians causes vehicles to delay and slow down their speed. In terms of pedestrian speed, the decrease was relatively minor and consistent across the scenarios. This was primarily due to drivers' adherence to giving full priority to pedestrians approaching the crosswalks, ensuring smoother pedestrian flow.

6.2.3 Average stops

The average number of stops serves as an important metric, representing the cumulative stops made by each individual vehicle or pedestrian during the analysis. This parameter is calculated by dividing the total count of stops performed by vehicles or pedestrians throughout the analysis process by the respective number of vehicles or pedestrians that entered the network. Figure 6.15 - Figure 6.17 display the change in the number of stops curve of vehicles, and Figure 6.18 - Figure 6.20 display the change in the number of stops curve of pedestrians at the MSSI according to the different scenarios.

Table 6.8 : The results of the average number of stops for vehicles at MSSI.

Scenarios	**Municipal Intersection**		**Sapak Intersection**		**Serdivan Intersection**	
	Number Stops		**Number Stops**		**Number Stops**	
	Morning	Evening	Morning	Evening	Morning	Evening
Current	0.81	2.22	7.03	7.02	6.02	9.74
Scenario 1	1.29	4.44	7.42	10.45	6.32	11.83
Scenario 2	2.48	8.67	7.91	11.99	6.91	12.63
Scenario 3	3.84	9.79	7.80	10.83	7.31	13.99
Scenario 4	5.14	10.08	8.44	10.28	8.04	14.31
Scenario 5	5.54	10.60	8.56	10.42	8.02	14.53

Table 6.9 : The results of the average number of stops for pedestrians at MSSI.

Scenarios	Municipal Intersection		Sapak Intersection		Serdivan Intersection	
	Number Stops		Number Stops		Number Stops	
	Morning	Evening	Morning	Evening	Morning	Evening
Current	0.55	0.66	1.77	2.47	0.53	0.63
Scenario 1	0.51	0.54	1.39	1.17	0.56	0.64
Scenario 2	0.46	0.50	1.35	0.99	0.56	0.61
Scenario 3	0.47	0.55	1.21	0.84	0.53	0.57
Scenario 4	0.50	0.60	1.25	0.74	0.48	0.54
Scenario 5	0.57	0.60	1.15	0.72	0.46	0.57

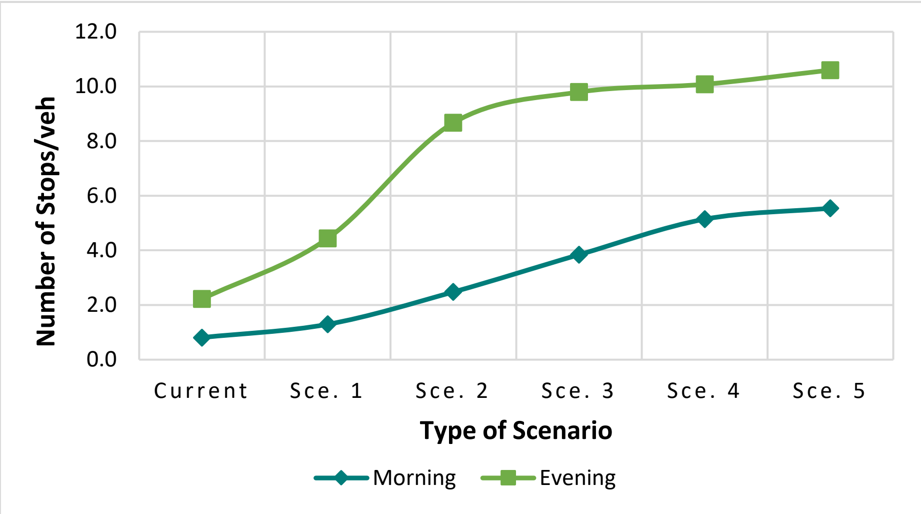

Figure 6.15 : The change in number of stops of vehicles at Municipality intersection.

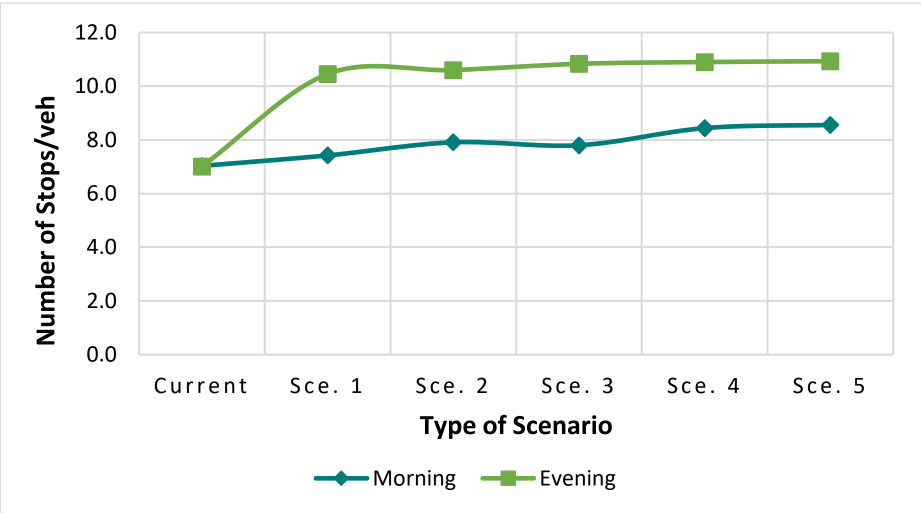

Figure 6.16 : The change in number of stops of vehicles at Sapak intersection.

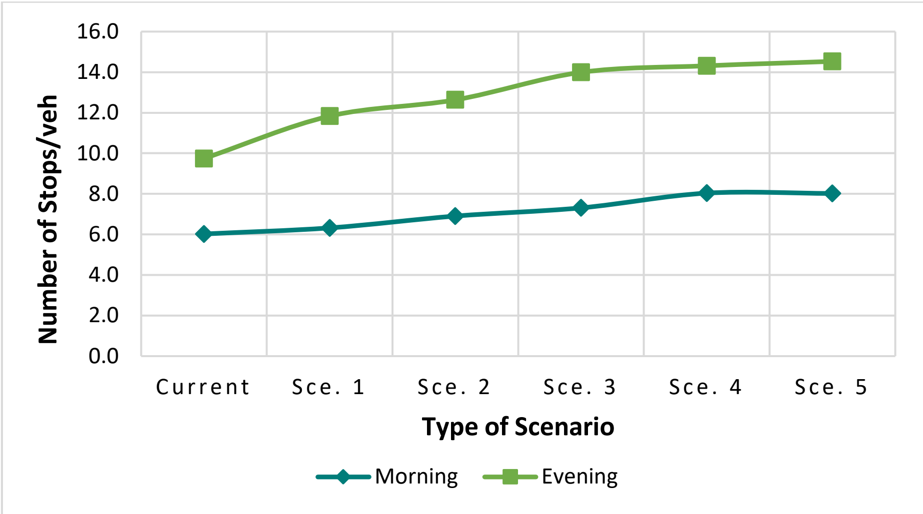

Figure 6.17 : The change in number of stops of vehicles at Serdivan intersection.

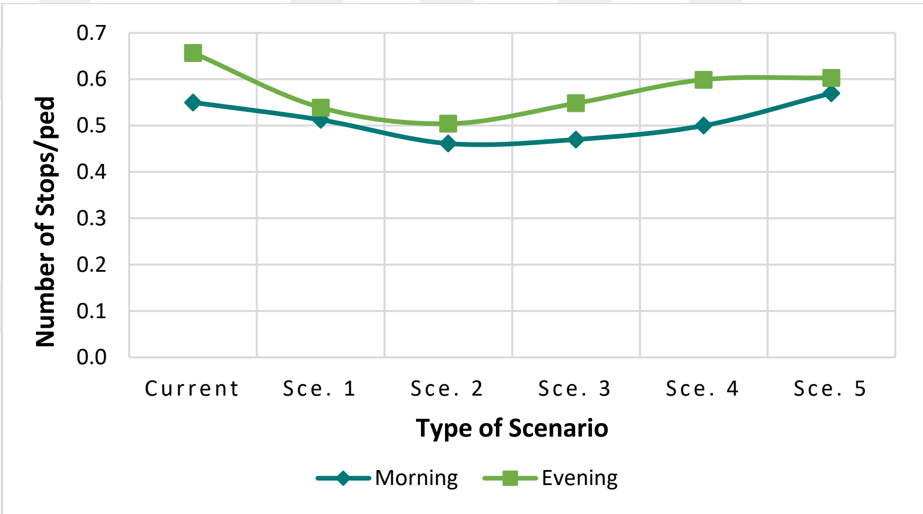

Figure 6.18 : The change in number of stops of pedestrians at Municipality intersection.

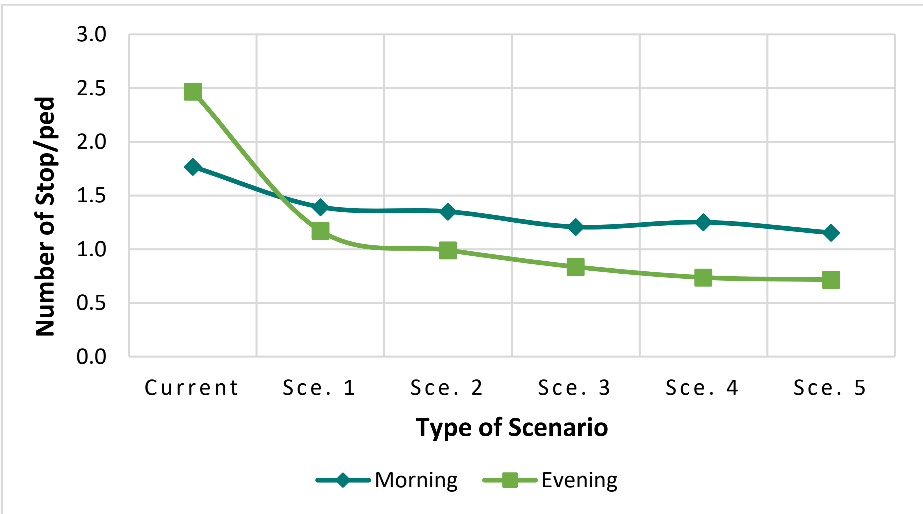

Figure 6.19 : The change in number of stops of pedestrians at Sapak intersection.

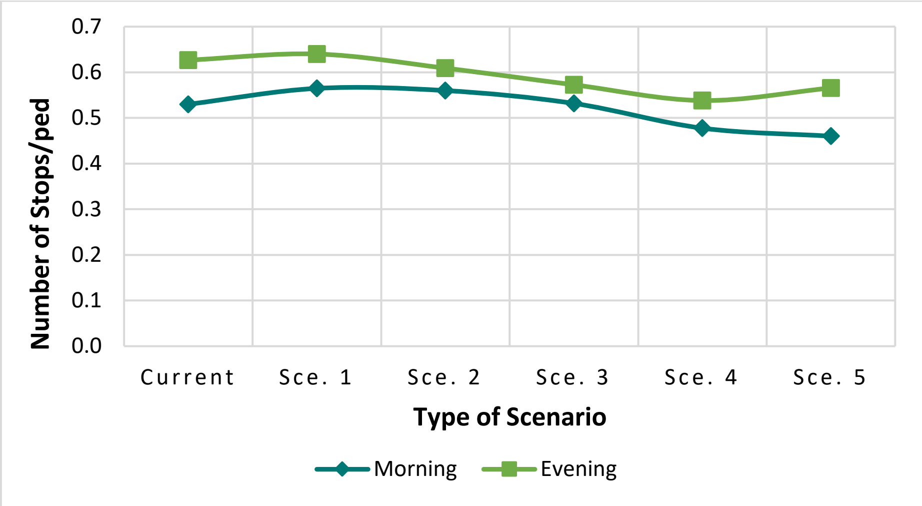

Figure 6.20 : The change in number of stops of pedestrians at Serdivan intersection.

The illustrations of the number of vehicle stops showed that both Sapak and Serdivan intersections have the highest ratio of stops per vehicle in the current traffic situation, as the number of vehicle stops in the morning and evening for both intersections ranged between 6 and 10 stops per vehicle. The number of vehicle stops at these intersections continued to increase with the rising pedestrian volume, peaking in scenario 5 at 8.56 stops per vehicle in the morning and 10.42 stops per vehicle in the evening for the Sapak intersection, and 8.02 stops per vehicle in the morning and 14.53 stops per vehicle in the evening for the Serdivan intersection. Conversely, the Municipality intersection experienced a lower number of stops per vehicle in the current traffic situation compared to the Sapak and Serdivan intersections. As the proportion of pedestrians ascended, correspondingly increased the number of stops per vehicle, and this increase was noticeable after scenario 1 until it reached, in scenario 5, 5.54 stops per vehicle in the morning and 10.60 stops per vehicle in the evening. Generally, the effect of the increase in pedestrian ratio on the number of stops for vehicles at the Sapak and Serdivan intersections was less than at the Municipality intersection, since the number of vehicle stops in the current traffic situation is high at these intersections and the increase in pedestrian ratio does not significantly affect the number of stops for vehicles as it does at the Municipality intersection. Pedestrian stops were minimal and rarely exceeded one stop per pedestrian, except at the Sapak intersection. However, overall, pedestrian stops were minimal and remained unaffected by the increase in pedestrian volume since vehicles give full priority to pedestrians.

6.2.4 Queue length (QL)

The queue length is measured upstream by the queue counter, and the maximum is thus calculated per time interval during simulation. Figure 6.21 - Figure 6.26 display the change in queue length for the four approaching legs at the MSSI according to the different scenarios.

Table 6.10 : The results of QL for vehicles in the morning at MSSI.

Scenarios	Municipal Intersection Queue Length (m)				Sapak Intersection Queue Length (m)				Serdivan Intersection Queue Length (m)			
	1	3	5	7	1	3	5	7	1	3	5	7
Current	12	0.2	4	9	40	77	87	66	1	81	183	0.4
Scenario 1	41	0.5	15	9	39	76	87	70	1	81	185	0.3
Scenario 2	62	0.3	28	20	37	77	86	72	2	80	186	0.5
Scenario 3	114	0.4	47	33	38	77	87	73	3	70	187	0.3
Scenario 4	123	0.7	97	24	37	79	87	72	4	73	186	0.8
Scenario 5	126	1.1	105	60	36	78	87	75	7	71	187	0.5

Table 6.11 : The results of QL for vehicles in the evening at MSSI.

Scenarios	Municipal Intersection Queue Length (m)				Sapak Intersection Queue Length (m)				Serdivan Intersection Queue Length (m)			
	1	3	5	7	1	3	5	7	1	3	5	7
Current	10	29	5	2	157	60	88	75	142	14	190	28
Scenario 1	28	63	20	3	150	80	87	76	154	19	190	8
Scenario 2	86	65	82	1	145	84	88	76	157	22	191	20
Scenario 3	89	66	91	1	139	85	88	76	160	34	192	59
Scenario 4	90	67	90	3	138	86	87	77	161	43	191	74
Scenario 5	91	67	98	8	135	86	87	77	162	41	191	90

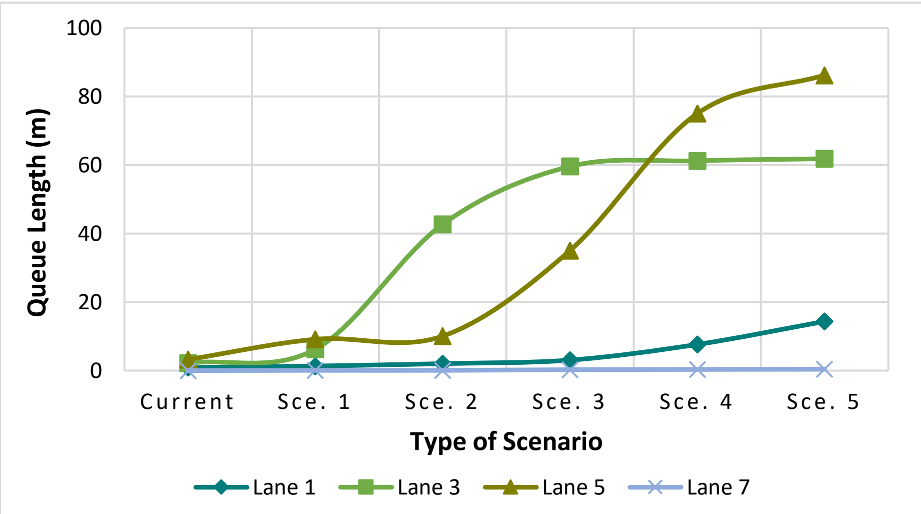

Figure 6.21 : The change in QL for vehicles in the morning at Municipality intersection.

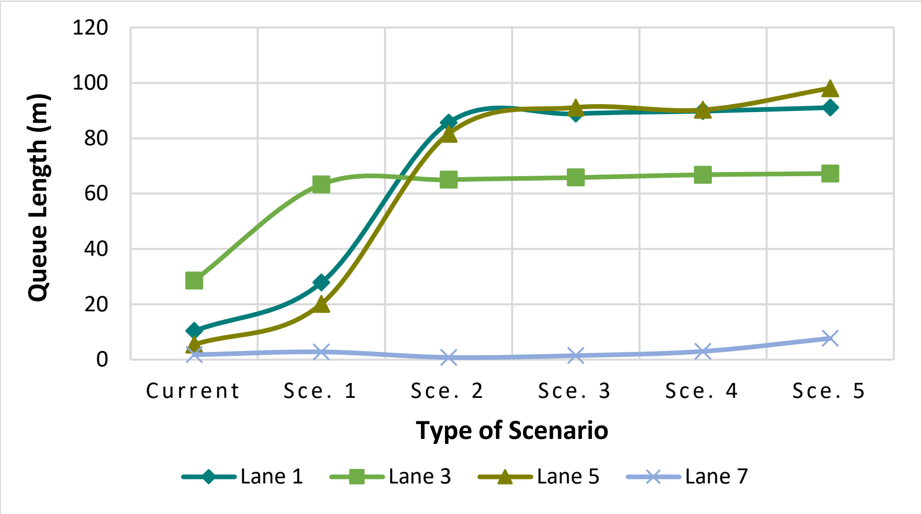

Figure 6.22 : The change in QL for vehicles in the evening at Municipality intersection.

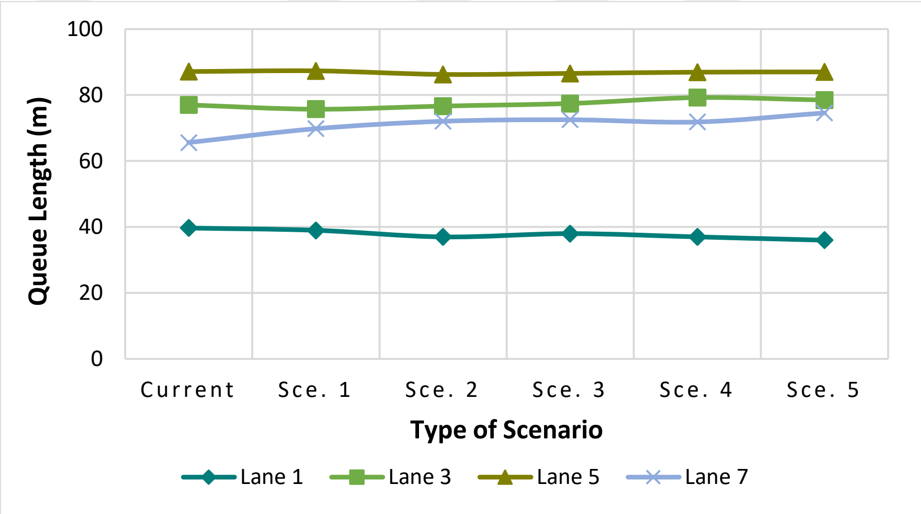

Figure 6.23 : The change in QL for vehicles in the morning at Sapak intersection.

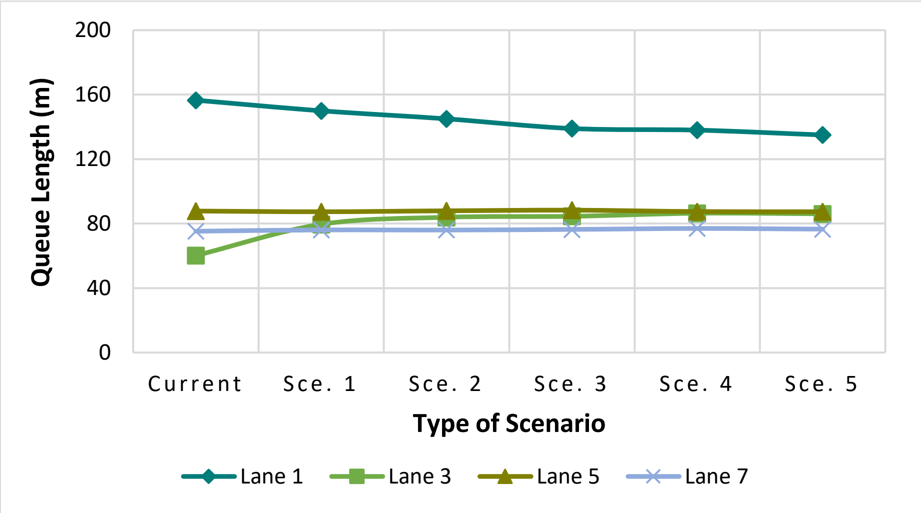

Figure 6.24 : The change in QL for vehicles in the evening at Sapak intersection.

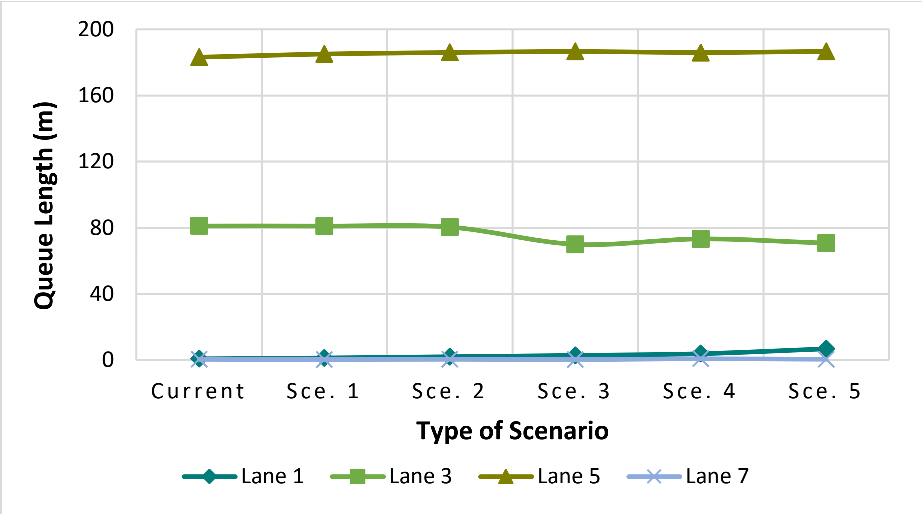

Figure 6.25 : The change in QL for vehicles in the morning at Serdivan intersection.

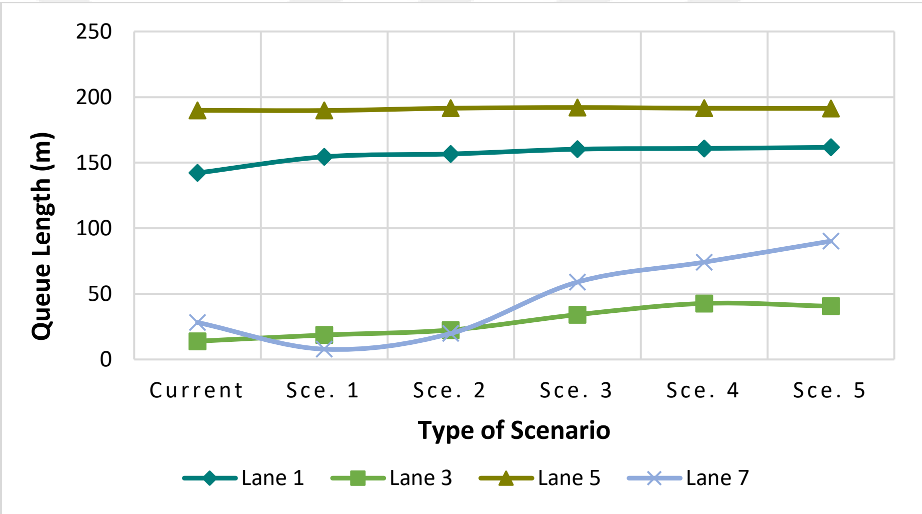

Figure 6.26 : The change in QL for vehicles in the evening at Serdivan intersection.

By examining the queue lengths at the approaching legs of the Sapak and Serdivan intersections, it is observed that these lengths are almost constant in most approaching legs at high values during the different scenarios, and these values are nearly equal to the lengths of the approaching legs drawn in the models, which means that these intersections experience heavy traffic volumes and queues extend along the majority of their approaching legs. On the contrary, at the Municipality intersection, the current traffic situation is characterized by smooth traffic flow and short queues. However, following Scenarios 1 and 2, there is a discernible increase in the lengths of queues at most approaching legs, which stabilize at semi-fixed lengths, which means that the intersection after these scenarios experiences heavy traffic volumes and queues extend along the majority of its approaching legs.

6.2.5 Emissions and fuel consumption

The quantity of emissions is calculated in grams per vehicle, and the fuel consumption is calculated in liters per vehicle. The emissions quantified include carbon monoxide (CO), nitrogen oxides (NOX), and volatile organic compounds (VOC). Figure 6.27 - Figure 6.29 illustrate the change in the quantity of emissions, and Figure 6.30 - Figure 6.32 illustrate the change in fuel consumption at the MSSI according to the different scenarios.

Table 6.12 : The results of emissions in the morning at MSSI.

Scenarios	Municipal Intersection Emissions (gm/veh)			Sapak Intersection Emissions (gm/veh)			Serdivan Intersection Emissions (gm/veh)		
	CO	NO_X	VOC	CO	NO_X	VOC	CO	NO_X	VOC
Current	0.88	0.17	0.20	5.06	0.98	1.17	4.26	0.83	0.99
Scenario 1	1.19	0.23	0.27	5.13	1.00	1.19	4.39	0.85	1.02
Scenario 2	1.99	0.39	0.46	5.39	1.05	1.25	4.68	0.91	1.09
Scenario 3	2.89	0.56	0.67	5.22	1.02	1.21	4.85	0.94	1.12
Scenario 4	3.73	0.72	0.86	5.50	1.07	1.28	5.21	1.01	1.21
Scenario 5	4.01	0.78	0.93	5.68	1.11	1.32	5.24	1.02	1.22

Table 6.13 : The results of emissions in the evening at MSSI.

Scenarios	Municipal Intersection Emissions (gm/veh)			Sapak Intersection Emissions (gm/veh)			Serdivan Intersection Emissions (gm/veh)		
	CO	NO_X	VOC	CO	NO_X	VOC	CO	NO_X	VOC
Current	1.77	0.34	0.41	4.74	0.92	1.10	5.98	1.16	1.39
Scenario 1	3.21	0.63	0.74	6.59	1.28	1.53	7.19	1.40	1.67
Scenario 2	5.86	1.14	1.36	7.37	1.43	1.71	7.58	1.48	1.76
Scenario 3	6.72	1.31	1.56	6.89	1.34	1.60	8.50	1.65	1.97
Scenario 4	7.22	1.40	1.67	6.87	1.34	1.59	9.03	1.76	2.09
Scenario 5	7.84	1.53	1.82	7.34	1.43	1.70	9.47	1.84	2.20

Table 6.14 : The results of fuel consumption at MSSI.

Scenarios	Municipal Intersection Fuel Consumption (L/veh)		Sapak Intersection Fuel Consumption (L/veh)		Serdivan Intersection Fuel Consumption (L/veh)	
	Morning	Evening	Morning	Evening	Morning	Evening
Current	0.05	0.10	0.14	0.35	0.27	0.26
Scenario 1	0.06	0.17	0.18	0.34	0.28	0.36
Scenario 2	0.11	0.32	0.19	0.41	0.29	0.40
Scenario 3	0.16	0.36	0.29	0.47	0.28	0.37
Scenario 4	0.20	0.39	0.37	0.52	0.30	0.37
Scenario 5	0.22	0.42	0.40	0.57	0.31	0.40

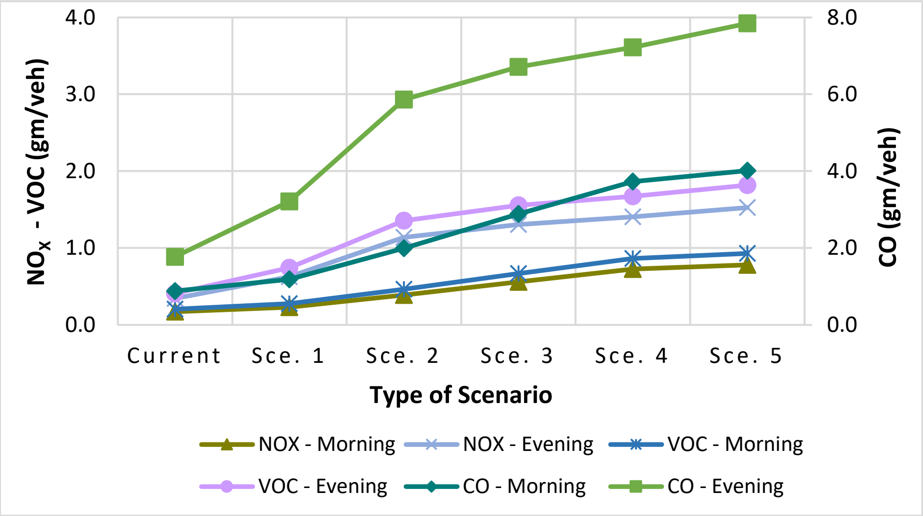

Figure 6.27 : The change in emissions at Municipality intersection.

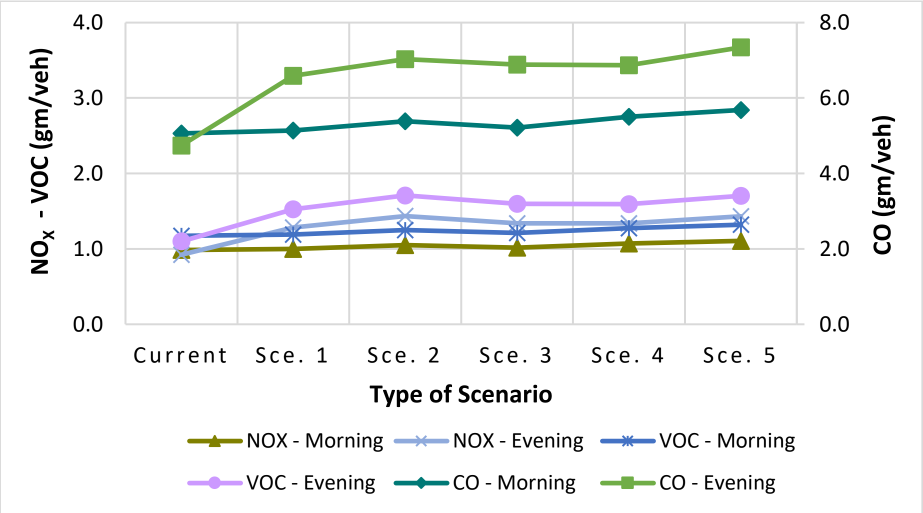

Figure 6.28 : The change in emissions at Sapak intersection.

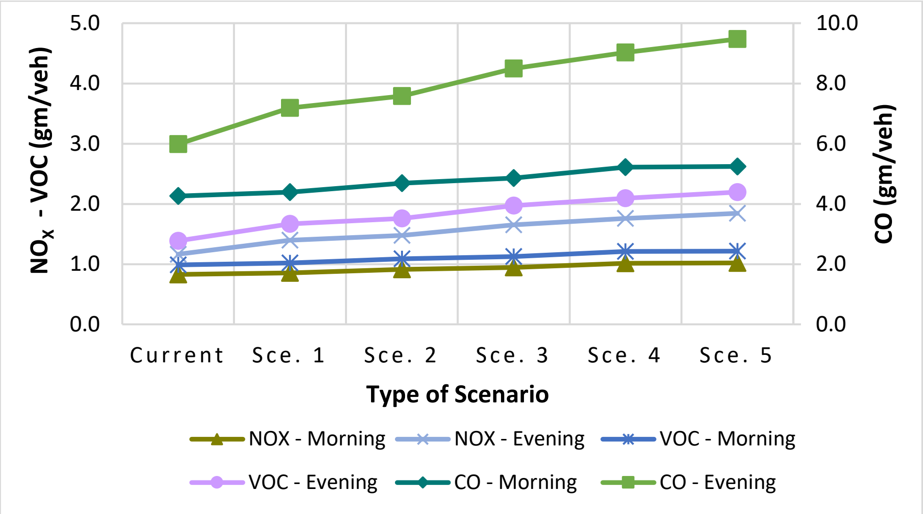

Figure 6.29 : The change in emissions at Serdivan intersection.

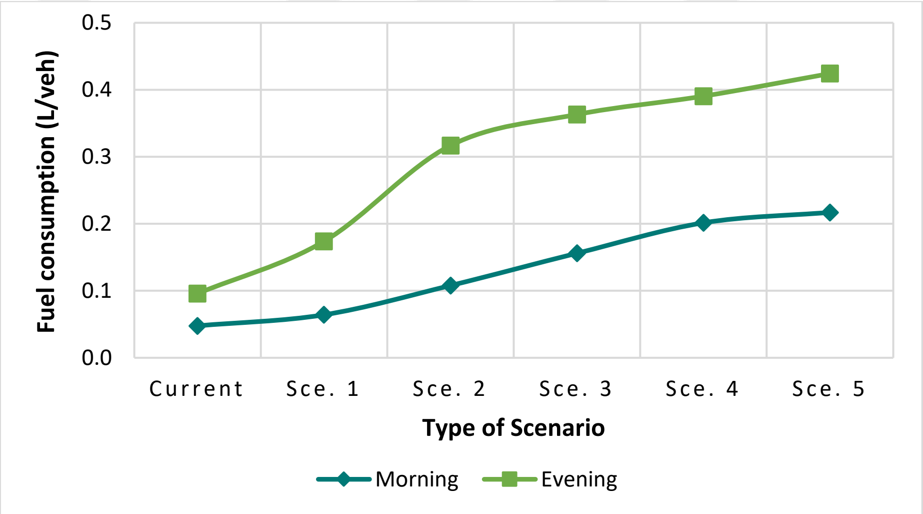

Figure 6.30 : The change in fuel consumption at Municipality intersection.

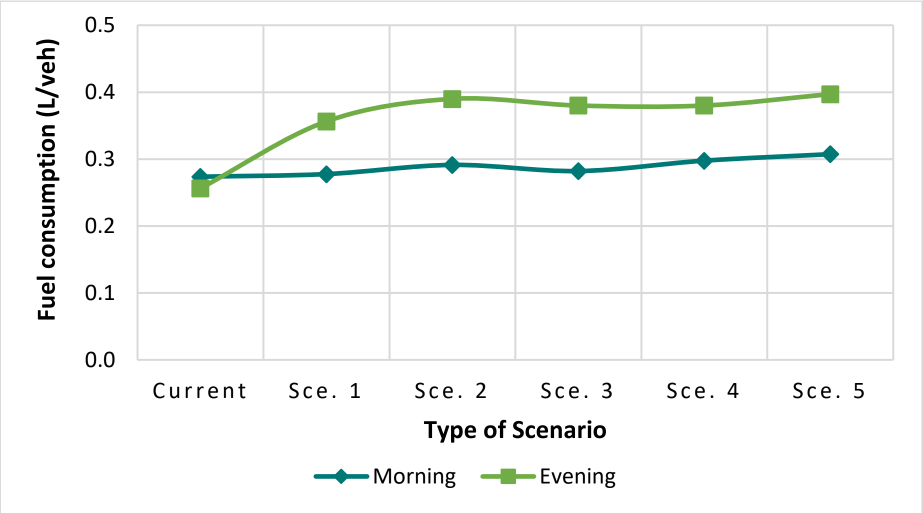

Figure 6.31 : The change in fuel consumption at Sapak intersection.

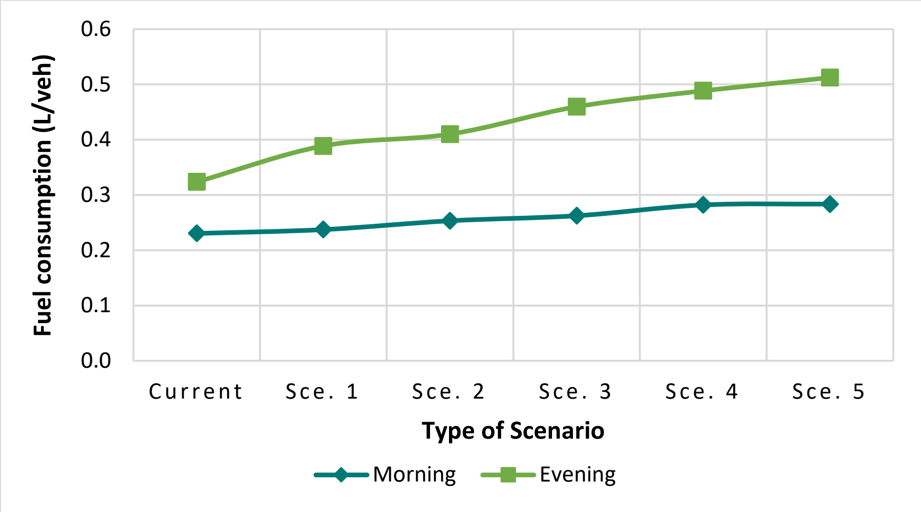

Figure 6.32 : The change in fuel consumption at Serdivan intersection.

Based on the graphs shown for emissions at the three intersections, carbon monoxide (CO) represents the most emitted gas, with levels almost twice as high as nitrogen oxides (NO_X) and volatile organic compounds (VOC). Sapak and Serdivan intersections exhibited the highest levels of emissions in the current traffic situation, attributable to the heavy traffic volumes in these areas. Although the increase in the pedestrian ratio had an effect on emissions, it was not as pronounced as observed at the Municipality intersection. At the Municipality intersection, emissions were low in the current traffic situation and increased in conjunction with the increasing proportion of pedestrians, but the largest shift in the amount of emissions was after scenario 1, after which the increase continued but in a smaller ratio compared to the previous increase. As for fuel consumption, the ratio of fuel consumed at the Sapak and Serdivan intersections was greater compared to that at the Municipality intersection in the current traffic situation. The rate of pedestrian increase also affects the fuel consumption at the three intersections, and the effect was evident in Municipality intersection after scenario 1.

6.3 Results of Vatan Intersection (VI)

The results are presented in this section for the two cases that were modeled and analyzed at the Vatan intersection: the typical case and the local case. The typical case implies that drivers give way to pedestrians in all situations, which in theory is expected to be the case for the vehicle-pedestrian relationship at unsignalized intersections. The local situation implies that drivers rarely give way to pedestrians and that vehicles take priority. While this is the case in most undeveloped and developing societies, it is not common for pedestrians to be given priority in Turkey.

Table 6.15 shows the volume of vehicles and pedestrians that enter the Vatan Intersection in the current traffic situation, and Figure 6.33 shows the change in the volume of vehicles during the increase in the volume of pedestrians according to different scenarios.

Table 6.15 : The current volumes of vehicles and pedestrians at VI.

Type of Traffic	Typical Case		Local Case	
	Morning	Evening	Morning	Evening
Vehicles	1097	1301	1097	1259
Pedestrians	290	710	290	710

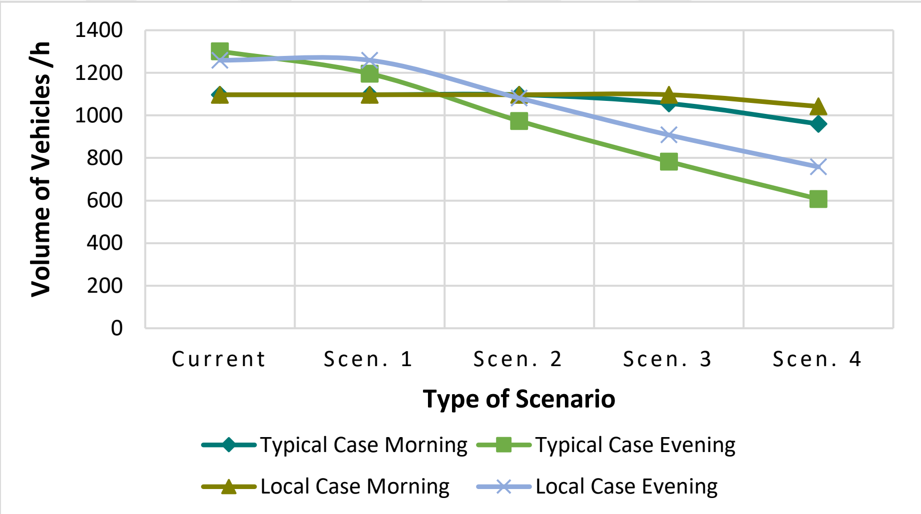

Figure 6.33 : The change in vehicle volumes at Vatan intersection.

The graphical analysis reveals that the variation in vehicles volume is greater in the typical case than in the local case in the different scenarios. This can be attributed to the fact that, in the typical case, vehicles give priority to pedestrians, leading to the formation of traffic queues and a lower number of vehicles entering the intersection. Conversely, in the local case, pedestrians yield to vehicles, waiting for an appropriate opportunity to cross, resulting in a lower number of vehicle stops at crosswalks and ultimately allowing more vehicles to enter the intersection unimpeded.

The results of the performance metrics at the three intersections are shown in Table 6.16 - Table 6.25.

6.3.1 Average delay and LOS

Figure 6.34 and Figure 6.35 show the change in delay and the level of service for vehicles, while Figure 6.36 and Figure 6.37 show the change in delay and the level of service for pedestrians at Vatan intersection for the typical and local cases according to the different scenarios.

Table 6.16 : The results of the average delay and LOS for vehicles at VI.

Type of Scenario	Typical Case				Local Case			
	Delay (s/ped)		LOS		Delay (s/ped)		LOS	
	Morning	Evening	Morning	Evening	Morning	Evening	Morning	Evening
Current	16.36	105.58	C	F	18.44	115.31	C	F
Scenario 1	33.44	129.64	D	F	21.17	121.98	C	F
Scenario 2	49.58	169.05	E	F	25.84	144.77	D	F
Scenario 3	91.23	221.22	F	F	54.90	179.63	F	F
Scenario 4	123.13	297.70	F	F	81.87	310.00	F	F

Table 6.17 : The results of the average delay and LOS for pedestrians at VI.

Type of Scenario	Typical Case				Local Case			
	Delay (s/ped)		LOS		Delay (s/ped)		LOS	
	Morning	Evening	Morning	Evening	Morning	Evening	Morning	Evening
Current	1.17	4.16	A	A	7.38	32.73	B	E
Scenario 1	1.41	3.09	A	A	10.25	35.90	C	E
Scenario 2	1.68	2.06	A	A	11.55	44.92	C	E
Scenario 3	1.91	1.87	A	A	20.10	96.81	D	F
Scenario 4	1.61	2.41	A	A	20.59	104.03	D	F

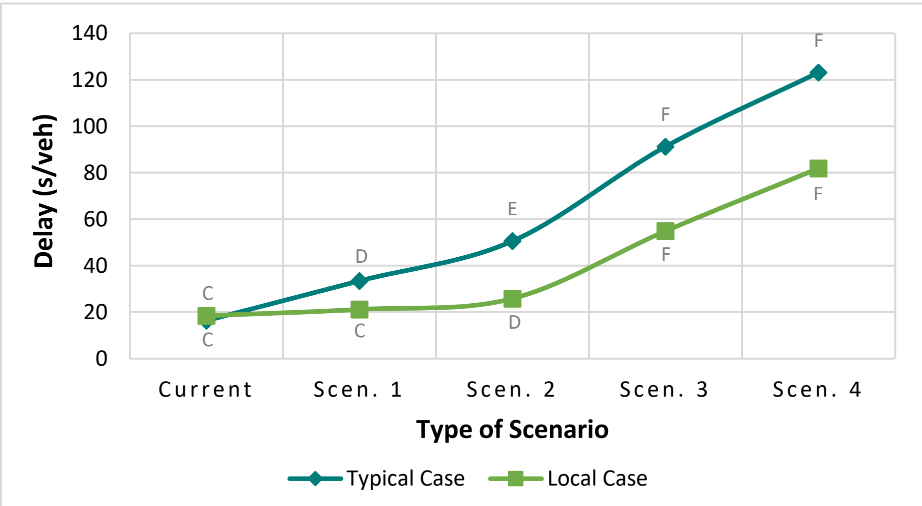

Figure 6.34 : The change in delay and LOS of vehıcles in the morning at VI.

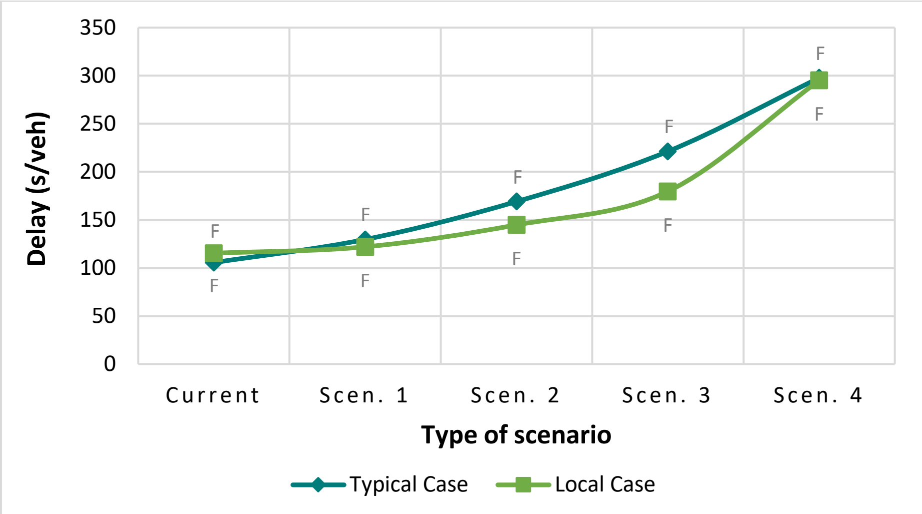

Figure 6.35 : The change in delay and LOS of vehıcles in the evening at VI.

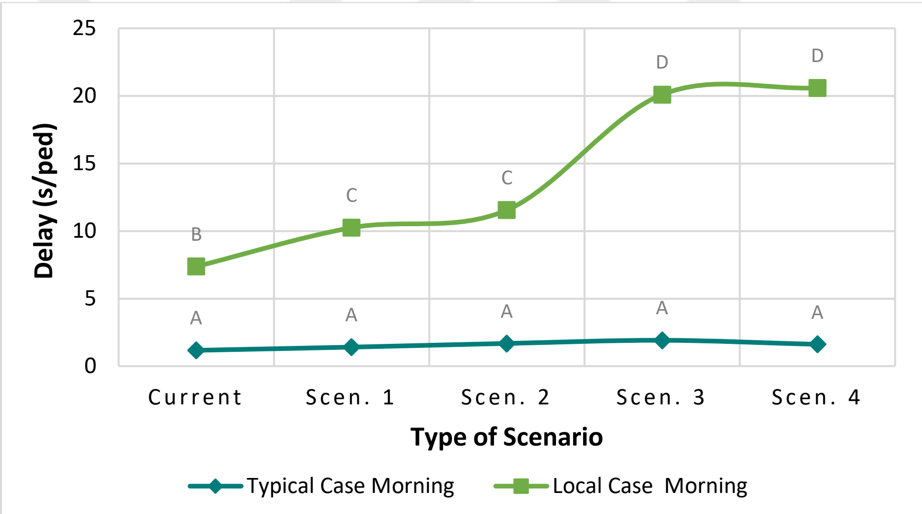

Figure 6.36 : The change in delay and LOS of pedestrians in the morning at VI.

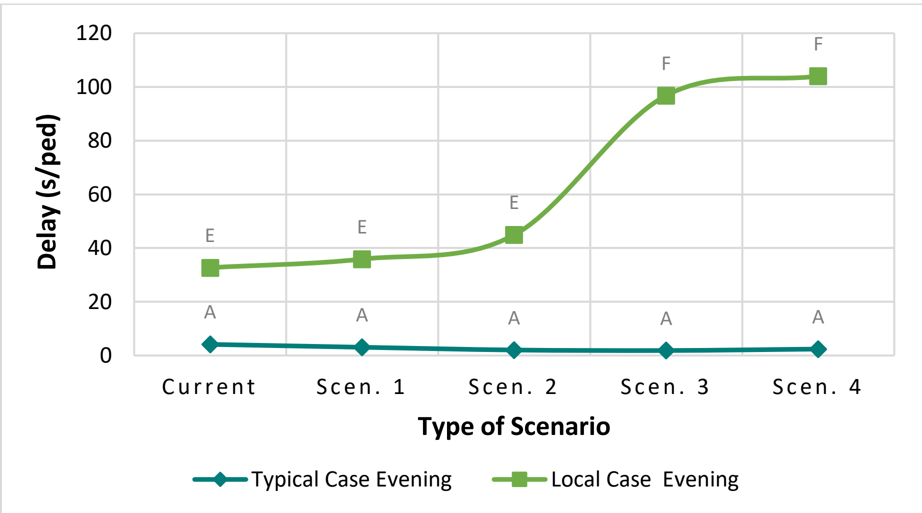

Figure 6.37 : The change in delay and LOS of pedestrians in the evening at VI.

According to the illustrations, it was evident that the typical case exhibited more favorable performance measures for pedestrians during both morning and evening peak hours, in which the delay values remained constant at low values and at level of service A, and this was a result of complying vehicles with pedestrians and giving them full priority. In contrast, the local case experienced high delay values, leading to a deterioration in the level of service, and scenario 2 represented a watershed, after which delay values increased substantially. On the other hand, the local case showed an improvement in delay values and level of service for vehicles. In the morning, the change in delay remained slight in both cases but became noticeable after scenario 2, deteriorating the level of service for F. In the evening, despite the improvement in the local case, the delay values for both cases were high, resulting in a level of service F in all scenarios.

6.3.2 Average speed

Figure 6.38 displays the change in the speed curve of vehicles, and Figure 6.39 displays the change in the speed curve of pedestrians at Vatan intersection for the typical and local cases according to the different scenarios.

Table 6.18 : The results of the average speed for vehicles at VI.

Type of Scenario	Typical Case		Local Case	
	Speed (km/veh)		Speed (km/veh)	
	Morning	Evening	Morning	Evening
Current	27.08	7.83	25.69	7.26
Scenario 1	19.70	6.52	24.04	6.87
Scenario 2	14.07	5.09	21.68	5.97
Scenario 3	9.00	3.94	13.32	4.90
Scenario 4	6.89	2.95	9.80	2.42

Table 6.19 : The results of the average speed for pedestrians at VI.

Type of Scenario	Typical Case		Local Case	
	Speed (km/ped)		Speed (km/ped)	
	Morning	Evening	Morning	Evening
Current	3.62	3.42	3.40	2.72
Scenario 1	3.55	3.50	3.34	2.66
Scenario 2	3.55	3.46	3.27	2.12
Scenario 3	3.51	3.42	3.10	1.35
Scenario 4	3.49	3.36	2.84	0.95

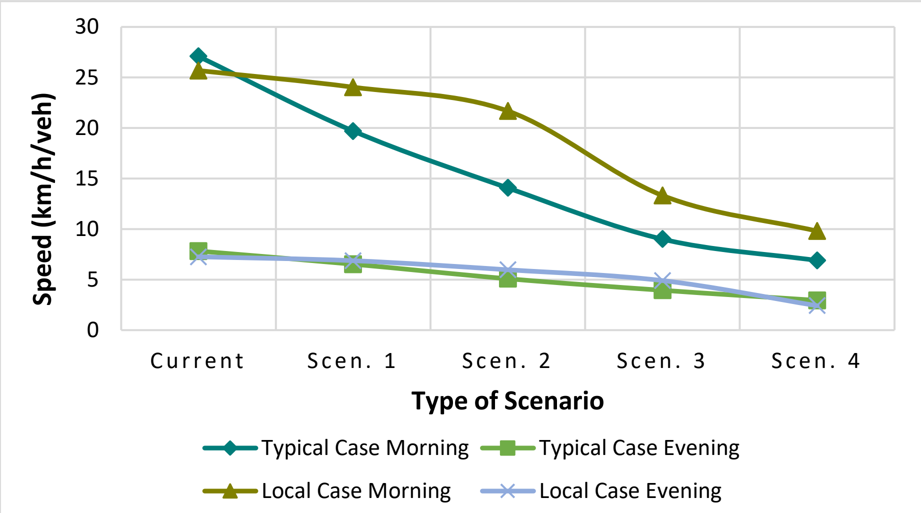

Figure 6.38 : The change in the speed of vehicles at VI.

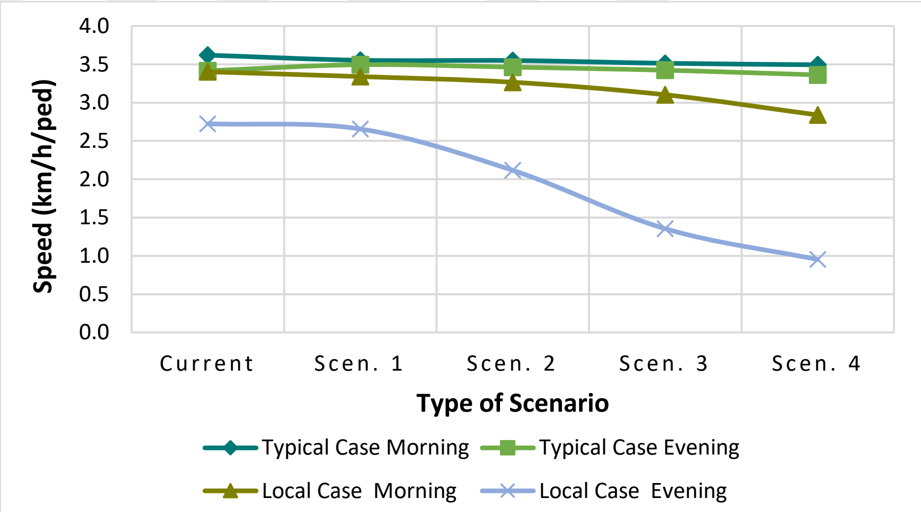

Figure 6.39 : The change in the speed of pedestrians at VI.

Based on the speed illustrations, it is evident that the typical case resulted in a significant improvement in pedestrian speed, as the values ranged from 3.62 km/h to 3.49 km/h in the morning and from 3.42 km/h to 3.36 km/h in the evening during the different scenarios. In contrast, the local case did not experience a considerable decrease in morning speed values compared to the typical case, but in the evening, the speed values dropped to 2.72 km/h and continued to decline, particularly after scenario 2, reaching as low as 0.95 km/h in scenario 4. With respect to vehicle speed, the local case exhibited better values, especially in the morning, as pedestrians in the local case do not have full priority and wait for a suitable gap in the flow of vehicles to cross. When comparing the speeds of vehicles and pedestrians in the morning and evening, it is apparent that the morning values are superior due to heavy traffic volumes in the evening. These findings highlight the significance of pedestrian priority in enhancing pedestrian speed and the complexities of traffic patterns.

6.3.3 Average stops

Figure 6.40 illustrates the change in the number of stops for vehicles, and Figure 6.41 illustrates the change in the number of stops for pedestrians at Vatan intersection for the typical and local cases e according to the different scenarios.

Table 6.20 : The results of the average number of stops for vehicles at VI.

Type of Scenario	Typical Case Speed (km/veh)		Local Case Speed (km/veh)	
	Morning	Evening	Morning	Evening
Current	4.15	10.92	5.45	13.49
Scenario 1	5.40	10.04	4.18	10.36
Scenario 2	4.99	11.02	2.63	9.80
Scenario 3	8.10	13.12	4.97	9.49
Scenario 4	10.53	13.52	7.55	8.50

Table 6.21 : The results of the average number of stops for pedestrians at VI.

Type of Scenario	Typical Case Speed (km/veh)		Local Case Speed (km/veh)	
	Morning	Evening	Morning	Evening
Current	0.41	1.41	0.76	2.06
Scenario 1	0.54	0.70	0.95	1.96
Scenario 2	0.49	0.49	1.00	6.01
Scenario 3	0.58	0.42	1.31	18.29
Scenario 4	0.50	0.45	2.01	28.24

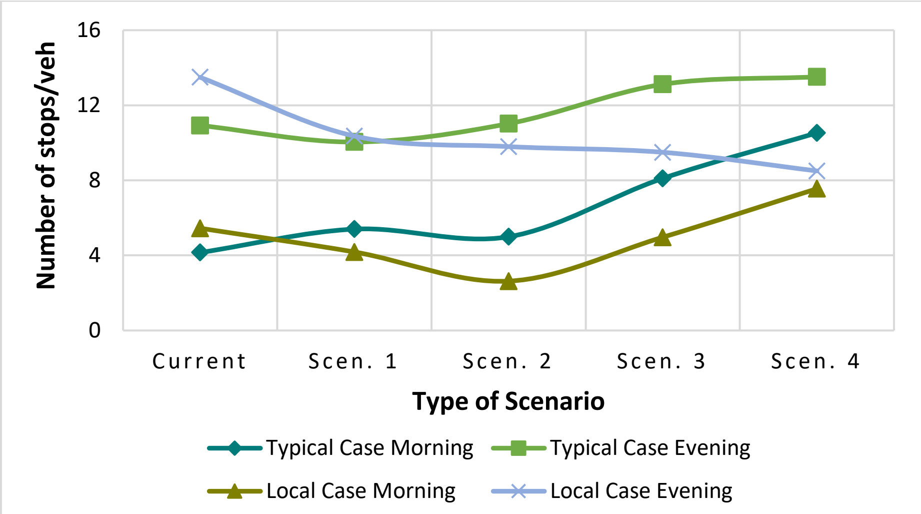

Figure 6.40 : The change in the number of stops of vehicles at VI.

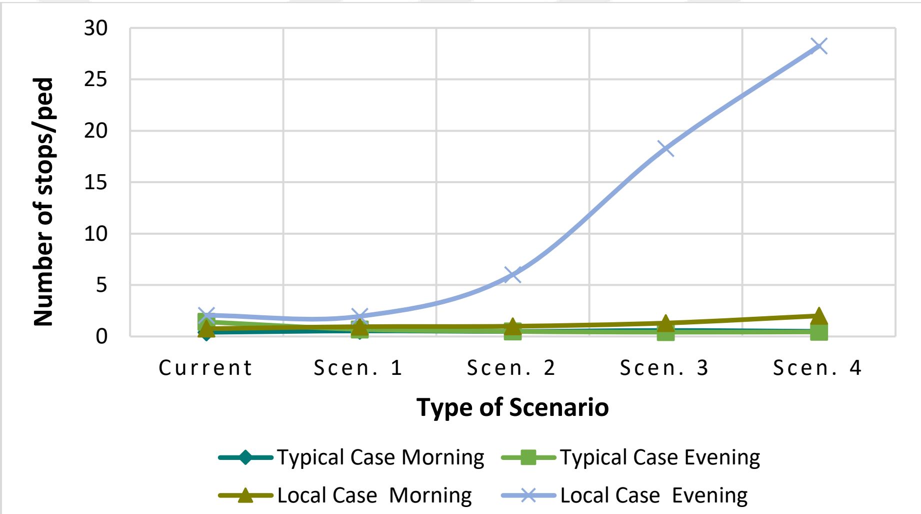

Figure 6.41 : The change in the number of stops of pedestrians at VI.

Based on the data and illustrations, the pedestrian movement was smooth in the typical case, with a negligible number of stops even with an increase in pedestrian volume during different scenarios. In the local case, the current traffic situation was relatively good, but the increase in pedestrian volume made them suffer from an increase in the number of stops. Although the increase was marginal during the morning peak hours, it became more pronounced in the evening, exhibiting a distinct upward trend after scenario 2, reaching a peak of 28.24 stops per pedestrian in scenario 4. The situation was different with regard to vehicles, in which the typical case showed a higher number of stops due to vehicles giving full priority to pedestrians, leading the number of stops to increase compared to the local case.

6.3.4 Queue length (QL)

Figure 6.42 - Figure 6.45 display the change in queue length for the four branches at Vatan intersection for the typical and local cases according to the different scenarios.

Table 6.22 : The results of QL for vehicles in the morning at VI.

Scenarios	Typical Case				Local Case			
	Queue Length (m)				Queue Length (m)			
	1	3	5	7	1	3	5	7
Current	12	0.2	4	9	15	0.2	6	9
Scenario 1	41	0.5	15	9	21	0.7	8	8
Scenario 2	62	0.3	28	20	20	0.1	9	17
Scenario 3	114	0.4	47	33	87	0.7	23	19
Scenario 6	123	0.7	97	40	116	0.3	41	21

Table 6.23 : The results of QL for vehicles in the evening at VI.

Scenarios	Typical Case				Local Case			
	Queue Length (m)				Queue Length (m)			
	1	3	5	7	1	3	5	7
Current	138	5	39	68	143	8	42	68
Scenario 1	144	3	94	68	142	6	90	67
Scenario 2	142	1	113	70	141	3	103	71
Scenario 3	145	3	117	71	142	5	110	69
Scenario 6	146	5	120	71	141	14	122	68

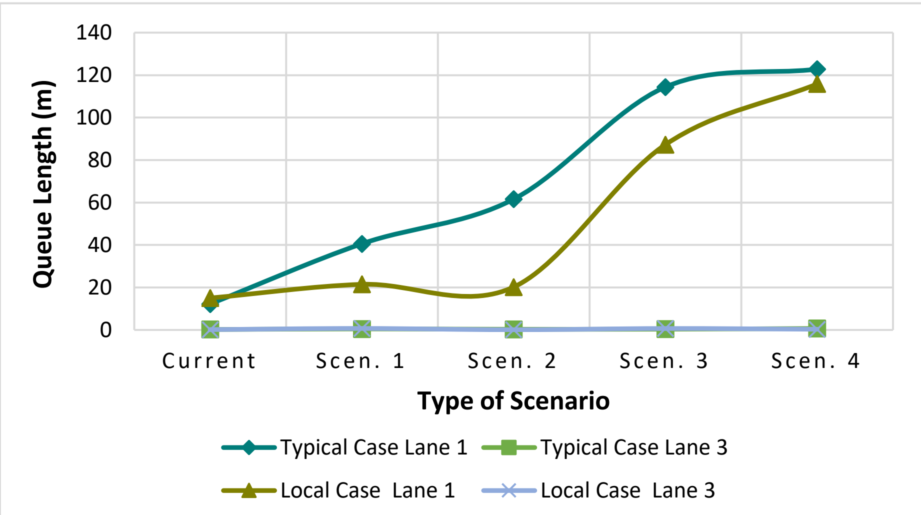

Figure 6.42 : The change in QL for vehicles in the morning at VI.

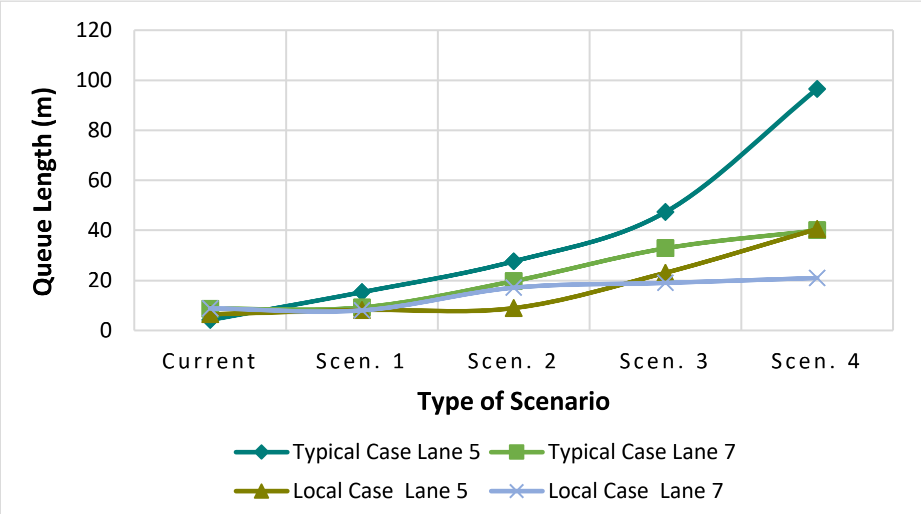

Figure 6.43 : The change in QL for vehicles in the morning at VI.

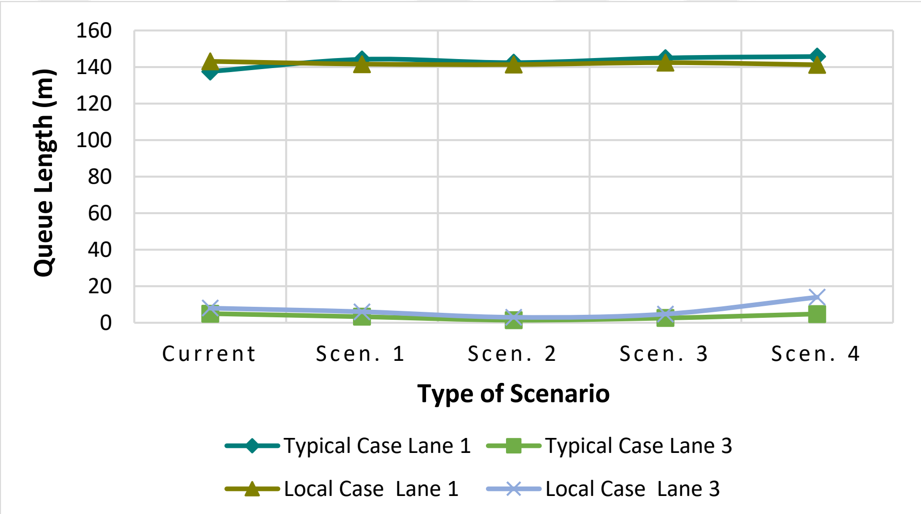

Figure 6.44 : The change in QL for vehicles in the evening at VI.

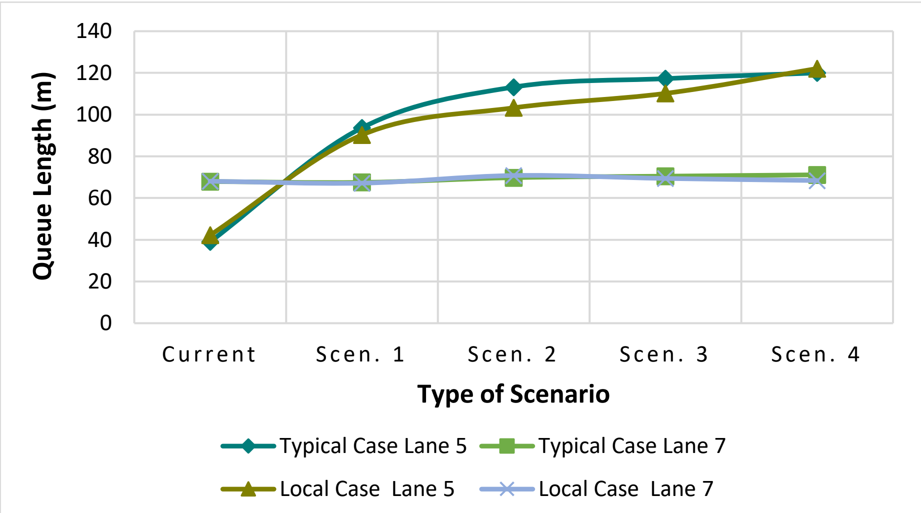

Figure 6.45 : The change in QL for vehicles in the evening at VI.

According to the data and illustrations, the queue lengths in the current traffic situation in the morning were within acceptable limits. In conjunction with the increase in the ratio of pedestrians, queues began to form significantly after scenario 2 in lanes 1 and 5. In lane 7, the queue length slightly increased, whereas in lane 3, no queue formed because of the low vehicle volumes. In the evening, there was no change in the length of the queues despite an increase in the ratio of pedestrians since the queues were already large in the current traffic situation and extended along the lanes. The lengths of the queues in the morning in the local case were better compared to the typical case due to the vehicles in the typical case stopping to give priority to pedestrians, therefore, queues formed, whereas there was no variation between the two cases in the evening due to the heavy traffic volumes.

6.3.5 Emissions and fuel consumption

Figure 6.46 - Figure 6.48 illustrate the change in the quantity of emissions, and Figure 6.49 illustrates the change in fuel consumption at Vatan intersection for the typical and local cases according to the different scenarios.

Table 6.24 : The results of emissions and fuel consumption in the morning at VI.

Scenarios	**Typical Case**				**Local Case**			
	Emissions (gm/veh)			**Fuel (L/veh)**	**Emissions (gm/veh)**			**Fuel (L/veh)**
	CO	NO_X	VOC		CO	NO_X	VOC	
Current	2.57	0.50	0.60	0.14	3.20	0.62	0.74	0.17
Scenario 1	3.39	0.66	0.79	0.18	2.65	0.52	0.61	0.14
Scenario 2	3.46	0.67	0.80	0.19	1.99	0.39	0.46	0.11
Scenario 3	5.37	1.04	1.24	0.29	3.37	0.66	0.78	0.18
Scenario 4	6.79	1.32	1.57	0.37	4.93	0.96	1.14	0.27

Table 6.25 : The results of emissions and fuel consumption in the evening at VI.

Scenarios	**Typical Case**				**Local Case**			
	Emissions (gm/veh)			**Fuel (L/veh)**	**Emissions (gm/veh)**			**Fuel (L/veh)**
	CO	NO_X	VOC		CO	NO_X	VOC	
Current	6.47	1.26	1.50	0.35	7.47	1.47	1.81	0.51
Scenario 1	6.35	1.24	1.47	0.34	6.53	1.27	1.51	0.35
Scenario 2	7.16	1.35	1.62	0.39	6.27	1.22	1.45	0.34
Scenario 3	8.77	1.71	2.03	0.47	6.15	1.20	1.42	0.33
Scenario 4	9.61	1.87	2.23	0.52	6.21	1.30	1.52	0.27

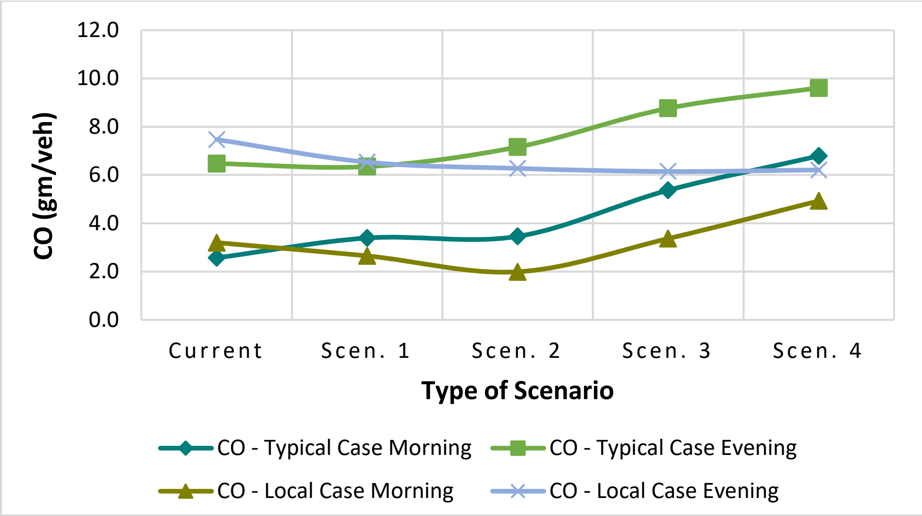

Figure 6.46 : The change in emissions of CO at VI.

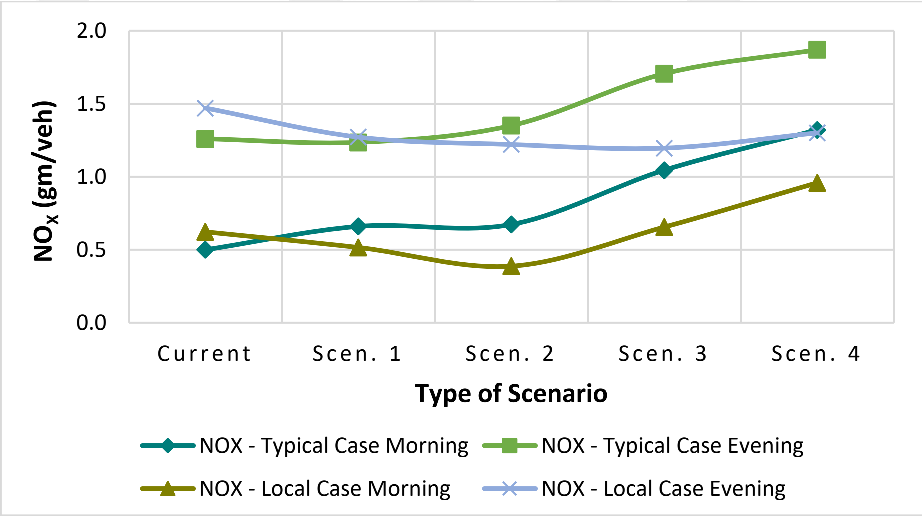

Figure 6.47 : The change in emissions of NO_X at VI.

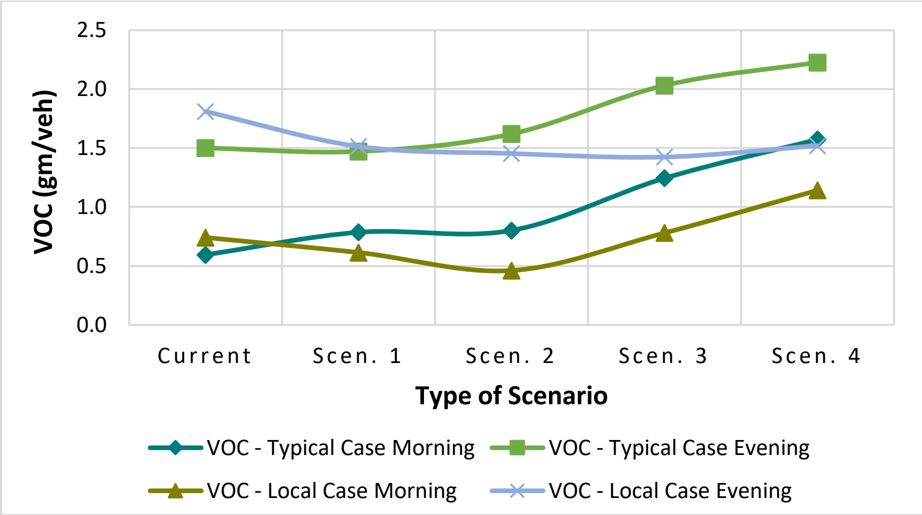

Figure 6.48 : The change in emissions of VOC at VI.

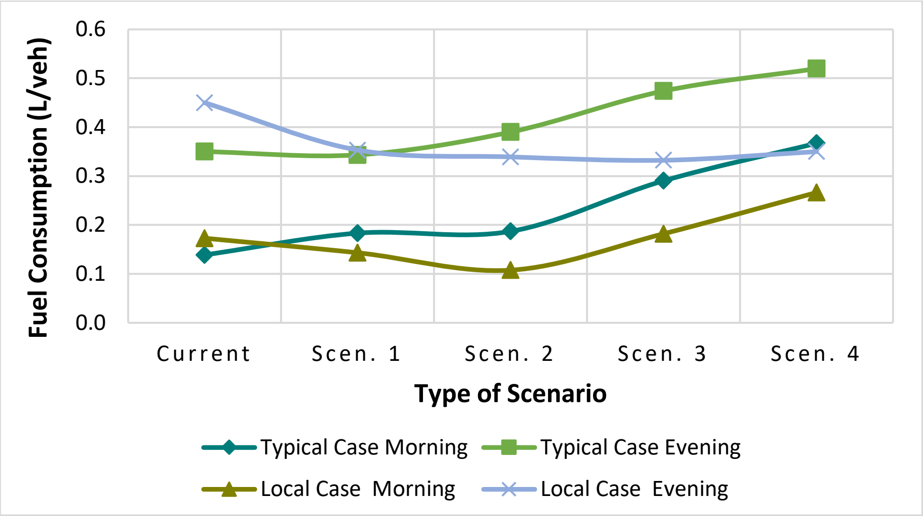

Figure 6.49 : The change in fuel consumption at VI.

Based on the presented illustrations, it is apparent that the typical case resulted in a significant increase in emissions and fuel consumption in comparison to the local case, especially in the last scenarios. While the difference between the two cases was marginal in the current traffic situation and scenario 1, it became more pronounced after scenario 2.

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

Climate change and its detrimental effects have increasingly captured the world's attention in the last decades, as many countries have sought to reduce these effects by shifting towards sustainable and resilient mobility options including active transportation. Efforts have been intensified to encourage walking and micromobility, specifically where urban mobility demand increased significantly in recent years. In parallel, infrastructure investments are supported by planning and financial support, and technological developments in this field are closely followed. The process of evaluating the infrastructure in light of the current traffic and the potential increase in pedestrian activity and micromobility in the changing trends represents an important step towards strengthening the efforts to encourage walking and shifting to pedestrian-friendly cities.

In this study, the effect of increasing pedestrian volume on the performance of four selected unsignalized intersections located near shopping malls and newly developed attraction centers was examined. It is predicted that the region will receive more active transportation modes in the near future owing to new developments in the area, people trying to avoid increasing traffic jams, and some external factors, including high fuel prices. The examination was conducted by gradually increasing the pedestrian volume without changing the current vehicular traffic and monitoring the intersection performance metrics. The assessment was carried out in a simulation environment using VISSIM software, and the study concluded the following:

The performance metrics of vehicular traffic at the Sapak and Serdivan intersections did not undergo sudden and significant deterioration with the incremental increase in pedestrian volume across the various scenarios. This can be attributed to the fact that these intersections were already experiencing compromised performance metrics in the existing traffic conditions, primarily due to the high volume of vehicular traffic and the relatively low presence of pedestrians. Consequently, the intersections had already been characterized by escalating delays, a decline in the level of service, increased instances of stops, elevated emissions, fuel consumption, longer queue lengths, and reduced speeds. The incremental increase in pedestrian volume had a slight and consistent effect on most performance metrics of vehicular traffic, however, it contributed to a further deterioration of the overall situation. For instance, in the morning peak hours, the percentage increase in delay during all scenarios compared to the current traffic conditions was 5.35% at the Sapak intersection and 10.29% at the Serdivan intersection, whereas the level of service deteriorated to F in all scenarios.

At the intersections that were experiencing low vehicular traffic and a fairly high volume of pedestrians, namely Municipality and Vatan intersections, the performance metrics for vehicular traffic initially maintained acceptable levels. However, with the increase in pedestrian volume, a sudden deterioration in intersection performance metrics was observed. At the Municipality intersection, the vehicle performance metrics were relatively good in the current traffic situation, conspicuously during morning peak hours, but the deterioration began noticeably and sharply after scenario 1 (a 200% increase in pedestrian volume), which means the traffic of vehicles remains acceptable within the possible increase in pedestrian volume up to 200%, after which the vehicular performance metrics noticeably deteriorate. Similarly, at the Vatan intersection, the traffic of vehicles in the morning peak hours remained at acceptable levels, and the performance metrics appeared logical in the current situation and scenario 1, but began to deteriorate significantly after scenario 2 (a 400% increase in pedestrian volume), which implies that vehicular traffic remaines within acceptable levels up to a 400% increase in pedestrian volume.. In the evening peak hours, the traffic of vehicles was already congested in the current situation, in which the performance metrics appeared to be deteriorating, and the situation was further worsened after scenario 2.

The evaluation of pedestrian traffic was a crucial aspect that demanded meticulous consideration. Pedestrian traffic remained normal, and the performance metrics yielded satisfactory results during all scenarios, provided that vehicles yielded to pedestrians approaching crosswalks and accorded them full priority to cross. Although this exemplified the desired and typical behavior in ideal conditions, this behavior was not observed in the study area, and similar patterns of behavior can be observed in developing and underdeveloped countries, including numerous cities in Turkey, where drivers often disregard yielding to pedestrians, particularly in areas characterized by high urban mobility. This tendency is particularly evident at unsignalized intersections, and even at signalized intersections, drivers frequently neglect the rule of giving way to pedestrians during right turns.

Thus, pedestrian performance metrics have been evaluated under two different cases: the local case, where vehicles typically did not comply with yielding to pedestrian rules, and the desired typical case, where vehicles adhered to the right of way for pedestrians. In the local case, pedestrian performance metrics exhibited a notable deterioration, particularly in the evening. This was evident at the Vatan intersection when comparing the local yielding behavior with the desired case, as the delay value increased from 32.37 s/ped in the current traffic conditions to 104.03 s/ped in scenario 4, at the same time the level of service deteriorated from E to F. Conversely, in the desired typical case, where vehicles adhered to yielding to pedestrians, the delay remained below 5 s/ped in all scenarios, maintaining a consistent level of service rating at A.

Considering the local mobility pattern and the study area's traffic conditions, the most critical conclusion of the study can be named as highlighting the importance of performing field measurements and analyzing the scenarios in a simulation environment to understand the local mobility behavior. Increasing the pedestrian volume gradually and monitoring the intersection performance metrics revealed identifying the breaking point for sudden detachment in the intersection performance metrics.

Based on the study's findings, urban planners and transportation engineers should prioritize the building of pedestrian-friendly infrastructure in areas with high urban mobility. Implementing crosswalks, sidewalks, and other amenities that promote safe and efficient pedestrian traffic is one example. Moreover, efforts should be made to create awareness among drivers and pedestrians about the need to yield to pedestrians and follow traffic rules in order to maintain safe mobility for all users. This can be accomplished by public awareness campaigns, education and training programs, and more stringent enforcement of traffic laws. By prioritizing such initiatives, urban planners and transportation engineers can work towards creating more livable and pedestrian-friendly urban environments.

Furthermore, further studies on this topic could concentrate on assessing the influence of pedestrian volume on signalized and other types of intersections. Additionally, more emphasis should be placed on the role of pedestrian conduct and attitudes regarding traffic rules and regulations, as these can have a considerable impact on intersection performance. Finally, efforts should be made to develop simulation tools and models that can effectively forecast the performance of intersections under various scenarios and conditions, thereby informing urban planning and transportation decision-making. Overall, this study makes an important contribution to the subject of urban mobility by emphasizing the importance of ongoing research and investment in pedestrian-friendly infrastructure and sustainable mobility options.

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APPENDICES

APPENDIX A. Vehicle and Pedestrian Flows of Municipality, Sapak and Serdivan Intersections

Table A.1: Vehicles flows at Municipality intersection.

Time	**Type of vehicle**	**1→8**	**1→6**	**1→4**	**3→2**	**3→8**	**3→6**	**5→4**	**5→2**	**5→8**	**7→6**	**7→4**	**7→2**
Morning	Motorbike	2	5	2	3	2	2	2	7	1	1	3	2
	Bus	0	9	8	6	0	2	3	8	0	0	1	0
	Truck	1	5	2	1	0	1	1	5	0	1	0	0
	Car	71	280	158	184	50	69	70	457	12	14	75	59
	Minibus	11	25	79	78	7	7	10	41	1	3	3	12
	Total	85	324	249	272	59	81	86	518	14	19	82	73
			658			412			618			174	
Evening	Motorbike	5	16	24	21	7	5	5	19	1	1	5	4
	Bus	1	8	3	6	0	2	1	6	0	0	0	0
	Truck	1	7	2	2	1	1	2	6	0	0	1	2
	Car	110	367	343	330	80	101	44	404	16	20	77	96
	Minibus	13	18	77	71	2	6	6	26	0	0	6	16
	Total	130	416	449	430	90	115	58	461	17	21	89	118
			995			635			536			228	

Table A.2: Pedestrian flows at Municipality intersection.

	Morning									**Evening**								
No. of lane	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Total**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Total**
1	0	1	6	2	0	13	3	3	27	0	0	16	6	0	27	6	4	59
2	1	0	14	4	4	1	1	11	35	0	0	25	13	16	3	2	13	72
3	8	21	0	0	0	0	1	3	32	11	37	0	0	3	0	4	7	61
4	1	6	1	0	6	3	8	0	24	2	8	0	0	21	17	25	0	73
5	3	27	16	24	0	0	6	0	75	2	26	13	27	0	0	7	1	74
6	17	2	0	0	0	0	4	0	24	24	5	2	12	0	0	12	6	60
7	2	1	0	14	4	3	0	0	23	3	4	4	39	9	16	0	0	73
8	7	13	11	0	0	0	0	0	32	4	14	10	1	0	12	0	0	40

Table A.3: Vehicles flows at Sapak intersection.

Time	Type of vehicle	1→8	1→6	1→4	3→2	3→8	3→6	5→4	5→2	5→8	7→6	7→4	7→2
Morning	Motorbike	0	8	2	5	7	2	6	15	2	1	16	1
	Bus	0	12	6	3	9	1	1	12	4	5	23	1
	Truck	3	4	3	3	11	4	3	3	1	3	14	2
	Car	23	127	104	92	612	174	169	399	179	65	741	13
	Minibus	8	58	31	23	95	29	23	132	40	35	175	10
	Total	34	209	146	126	734	210	202	561	226	109	969	27
			389			1070			989			1105	
Evening	Motorbike	1	31	13	15	22	7	26	35	17	7	29	3
	Bus	0	6	2	4	10	2	1	12	2	3	10	1
	Truck	2	6	3	4	14	6	5	5	4	1	19	1
	Car	89	447	150	233	999	298	169	456	268	113	1093	40
	Minibus	5	60	12	40	132	54	21	101	47	15	65	7
	Total	97	550	180	296	1177	367	222	609	338	139	1216	52
			827			1840			1169			1407	

Table A.4: Pedestrian flows at Sapak intersection.

	Morning									Evening								
No. of lane	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Total**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Total**
1	0	0	3	1	0	13	9	1	26	0	0	2	0	0	52	4	0	58
2	0	0	4	3	6	0	0	3	15	0	0	23	9	14	0	0	4	49
3	1	8	0	1	2	3	0	2	16	2	25	0	1	8	0	0	13	48
4	0	1	0	0	4	0	2	0	7	0	12	1	0	7	0	0	0	20
5	0	13	5	7	0	0	2	0	26	0	17	12	8	0	0	0	0	37
6	12	0	0	0	0	0	5	4	21	44	0	0	0	0	0	20	10	73
7	3	0	0	2	0	5	0	0	10	8	0	0	0	0	11	0	0	19
8	1	1	2	0	0	3	0	0	6	0	8	10	0	0	3	0	0	20

Table A.5: Vehicles flows at Serdivan intersection.

Time	Type of vehicle	1→8	1→6	1→4	3→2	3→8	3→6	5→4	5→2	5→8	7→6	7→4	7→2
Morning	Motorbike	1	10	1	0	9	2	4	17	6	1	4	3
	Bus	2	13	1	1	5	1	1	22	2	0	4	3
	Truck	2	7	1	0	1	5	2	8	0	1	1	2
	Car	50	519	49	102	203	198	107	979	113	46	74	110
	Minibus	8	113	8	5	24	17	20	148	19	9	28	9
	Total	63	662	60	108	242	223	134	1174	140	57	111	127
			785			573			1448			295	
Evening	Motorbike	5	28	9	5	15	5	4	25	11	6	16	10
	Bus	1	9	1	0	4	1	0	9	0	0	3	2
	Truck	2	16	1	2	1	9	9	16	1	1	2	1
	Car	172	857	304	73	226	203	139	795	264	179	233	150
	Minibus	17	120	20	4	29	27	24	121	22	19	25	10
	Total	197	1030	335	84	275	245	176	966	298	205	279	173
			1562			604			1440			657	

Table A.6: Pedestrian flows at Serdivan intersection.

	Morning									Evening								
No. of lane	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Total**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Total**
1	0	3	2	1	1	5	1	6	18	0	5	5	0	2	11	2	14	38
2	0	0	3	0	1	0	0	3	7	1	0	10	2	9	0	0	7	29
3	2	7	0	0	0	0	0	5	14	6	12	0	0	0	0	0	14	33
4	0	1	0	0	2	2	2	0	7	1	3	0	0	6	1	2	2	14
5	0	8	1	2	0	2	3	2	17	2	9	2	7	0	1	8	27	54
6	3	0	0	1	0	0	10	1	15	4	0	0	2	0	0	27	7	40
7	0	0	0	2	4	9	0	0	15	0	1	0	9	14	30	0	0	54
8	7	11	2	0	1	1	0	0	22	10	18	18	3	8	5	0	0	62