Estimation Of Saturation Flow Rate at Signalized Intersection Under Heterogeneous Traffic Conditions

By

Muhammad Umar Goraya

(Fall 2019-MSTN 00000318037)

Department of Transportation Engineering

NUST Institute of Civil Engineering

School of Civil and Environmental Engineering

National University of Sciences & Technology (NUST)

Islamabad, Pakistan

(2023)

Estimation of Saturation Flow Rate at Signalized Intersection Under Heterogeneous Traffic Conditions

By

Muhammad Umar Goraya

(Fall 2019-MSTN 00000318037)

A thesis submitted to the National University of Sciences and Technology, Islamabad, in partial fulfillment of the requirements for the degree of

Master of Science in

Transportation Engineering

Thesis Supervisor: Dr. Kamran Ahmed

NUST Institute of Civil Engineering

School of Civil and Environmental Engineering

National University of Science & Technology (NUST)

Islamabad, Pakistan.

THESIS ACCEPTANCE CERTIFICATE

It is certified that final copy of MS thesis written by Mr. Muhammad Umar Goraya Registration No. 00000318037 of MS Transportation Engineering, SCEE (NICE), has been vetted by undersigned, found completed in all respects as per NUST Statutes/Regulations, is free of plagiarism, errors, and mistakes and is accepted as partial fulfilment for award of MS degree.

Signature: ______________

Supervisor: Dr. Kamran Ahmad

Date: 31.8.2023

Signature (HoD): HoD Transportation Engineering, NUST Institute of Civil Engineering, School of Civil & Environmental Engineering, National University of Sciences and Technology

Date: 31.8.2023

Signature (Associate Dean, NICE) Dr. S. Muhammad Jamil, Associate Dean, NICE, SCEE, NUST

Date: 31/8/2023

Signature (Principal & Dean): PROF DR MUHAMMAD IRFAN, Principal & Dean, SCEE, NUST

Date: 31 AUG 2023

Form TH-4

National University of Sciences and Technology

MASTER'S THESIS WORK

We hereby recommend that the dissertation prepared under our Supervision by: (Student Name: Muhammad Umar Goraya & Regn No.00000318037)

Titled: **Estimation of Saturation Flow Rate at Signalized Intersection Under Heterogeneous Traffic Conditions**

be accepted in partial fulfillment of the requirements for the award of **Master of Science** degree with (B Grade).

Examination Committee Members

1. Name: Dr. Arshad Hussain Signature: ____________

2. Name: Dr. Sameer Ud Din Signature: ____________

Supervisor's name: Dr. Kamran Ahmed Signature: ____________

Date: 30/8/2023

____

Head of Department

HoD Transportation Engineering
NUST Institute of Civil Engineering
School of Civil & Environmental Engineering
National University of Sciences and Technology

Date: ____________

COUNTERSIGNED

Date: 31 AUG 2023

Principal & Dean

PROF DR MUHAMMAD IRFAN
Principal & Dean
SCEE, NUST

Author's Declaration

I Muhammad Umar Goraya hereby state that my MS thesis titled "Estimation of Saturation Flow Rate at Signalized Intersection Under Heterogeneous Traffic Conditions" is my own work and has not been submitted previously by me for taking any degree from this University National University of Science and Technology, Islamabad or anywhere else in the country/ world.

At any time if my statement is found to be incorrect even after I graduate, the university has the right to withdraw my MS degree.

Name of Student: Muhammad Umar Goraya

Date: 25/08/2023

Plagiarism Undertaking

I solemnly declare that research work presented in the thesis titled "Estimation of Saturation Flow Rate at Signalized Intersection Under Heterogeneous Traffic Conditions" is solely my research work with no significant contribution from any other person. Small contribution/ help wherever taken has been duly acknowledged and that complete thesis has been written by me.

I understand the zero-tolerance policy of the HEC and National University of Science and Technology, Islamabad towards plagiarism. Therefore, I as an author of the above titled thesis declare that no portion of my thesis has been plagiarized and any material used as reference is properly referred/cited.

I undertake that if I am found guilty of any formal plagiarism in the above titled thesis even after award of MS degree, the University reserves the rights to withdraw/revoke my MS degree and that HEC and the University has the right to publish my name on the HEC/University website on which names of students are placed who submitted plagiarized thesis.

Student/Author Signature: ____________

Name: Muhammad Umar Goraya

Dedicated

To

MY PARENTS & SIBLINGS

Acknowledgments

In the name of ALLAH, the Merciful, the Compassionate”.

All glory be to Allah, the Almighty, who gave me the strength to submit my thesis. All due respect to His Holy Prophet (SAW), whose teachings serve as a reliable source of information and direction for the whole human race.

I want to start by expressing my gratitude to my parents, who have always provided me with emotional support and been the inspiration for all I do. I owe a debt of gratitude to my research advisor, Dr. Kamran Ahmed for his insightful comments, support, encouraging leadership, notable recommendations, keen attention, and cordial exchanges that helped me finish this thesis. He gave generously of his time to guide me and assist me in finishing my thesis. Without his patient instruction, kind patronization, honest mentoring, and constant consultation, I would not have been able to effectively finish this challenging task.

Finally, I'd like to thank the National University of Science and Technology's NUST Institute of Civil Engineering, NICE, for its support. I would like to extend my appreciation to the support personnel of the department for their exceptional assistance during the project's execution. I express my sincere appreciation and blessings to all individuals who provided assistance during the process of completing this thesis.

(Muhammad Umar Goraya)

TABLE OF CONTENTS

List of Tables

List of Figures

List of Acronyms

SFR	Saturation Flow Rate
PCU	Passenger Car Unit
LOS	Level of Service
HCM	Highway Capacity Manual
FFS	Free Flow Speed
TRB	Transportation Research Board
PT	Peak Hour Traffic
Vphpl	Vehicle per hour per lane
IRC	Indian Roads Congress
BSFR	Base Saturation Flow Rate
FHWA	Federal Highway Administration
TPH	Traffic per Hour

Abstract

Evaluating the size and characteristics of traffic flow in emerging countries poses challenges due to the diverse range of traffic conditions present. The intersection is a crucial component within transportation networks since it significantly enhances the overall efficiency of the road network. The main objective is to precisely determine the saturation flow rate (SFR) at intersections in Faisalabad's urban area, considering the city's specific traffic challenges, such as the high number of two- and three-wheeled vehicles and issues with lane discipline. The average headway method is a widely recognized approach for accurately determining flow rate. It is commonly employed to estimate the SFR based on traffic data specific to intersections. The findings of this analysis demonstrate a Saturation flow rate of 1737 vehicles per hour per lane (vphpl), a quantity that holds considerable implications for the decision-making processes of traffic engineers and urban planners. This study highlights the importance of understanding the intricate traffic dynamics in Faisalabad to develop effective traffic management strategies that can effectively navigate the challenging road conditions. The interaction between regular vehicular motion and the unpredictable maneuvering of two- and three-wheeled vehicles that deviate from defined lanes has significant safety consequences. This research is noteworthy for its comprehensive methodology, which includes extensive fieldwork, video recordings, surveys, and observations to collect substantial data. The study at hand provides practical guidance to traffic engineers, urban planners, and policymakers by leveraging a comprehensive understanding of SFR and intricate traffic patterns.

Keywords: Saturation Flow Rate, Saturation Headway, highway capacity manual, Vehicle per hour per lane (vphpl), Random Maneuvering, Video Recordings

CHAPTER 1: INTRODUCTION

1.1 Preamble

Transport is crucial for the growth and development of nations. Efficient transportation of people and goods is crucial for driving economic progress, trade, and social development. Transport systems in developing countries are facing challenges in meeting the rising demand due to the substantial growth in the global population. Urbanization has led to an influx of individuals migrating to cities in pursuit of improved economic opportunities, thereby necessitating the development of enhanced transportation systems. Cities are experiencing increased congestion and strained transportation systems, which have negative impacts on the environment, economy, and quality of life.

Emerging economies encounter significant obstacles in establishing a dependable transport infrastructure that adequately caters to the demands of their populace. Insufficient infrastructure investment, along with obsolete and ineffective transportation systems, hinders progress.

Transport systems face challenges that extend beyond the mere development of infrastructure. Traffic congestion, pollution, and traffic accidents significantly impede the development of transportation systems. Investing in improved transport infrastructure is crucial for promoting long-term economic growth and social development in numerous countries globally. Moreover, the proliferation of unregistered vehicles has exacerbated the issue in numerous nations, placing additional strain on transportation infrastructure.

Faisalabad is a highly populated city known for its flourishing textile industry. The city is encountering difficulties in effectively managing the growing traffic volume, resulting in strain on the current infrastructure. Insufficient road infrastructure is causing congestion, delays, and accidents due to the increasing volume of vehicles. Furthermore, the escalation of heavy traffic has led to an increase in air pollution and noise pollution, resulting in detrimental effects on both the environment and public health.

Studying the saturation flow rate in Faisalabad is crucial for enhancing and advancing the city's transport system. It aids in the development of efficient traffic signal timings, optimization of road capacity, and enhancement of overall traffic management. To overcome these challenges, it is crucial to ascertain the saturation flow rate of key intersections in Faisalabad. This can be accomplished by choosing suitable intersections that accurately reflect the varied traffic patterns within the city. The study focuses on selecting the intersections that are heavily utilized and experience high volumes of traffic.

The intersections that could be considered for the study are Jinnah Colony Square, Railway Square, Khurrianwala Square, Allied Hospital Square, Stadium Square, and Chenab Square. These intersections depict various traffic patterns and offer valuable insights into the saturation flow rate of diverse traffic in Faisalabad.

Determining the saturation flow rate of intersections is crucial for city planners and traffic engineers to make well-informed decisions regarding traffic management and infrastructure development. This will enhance the efficiency, safety, and environmental sustainability of the transport system in Faisalabad.

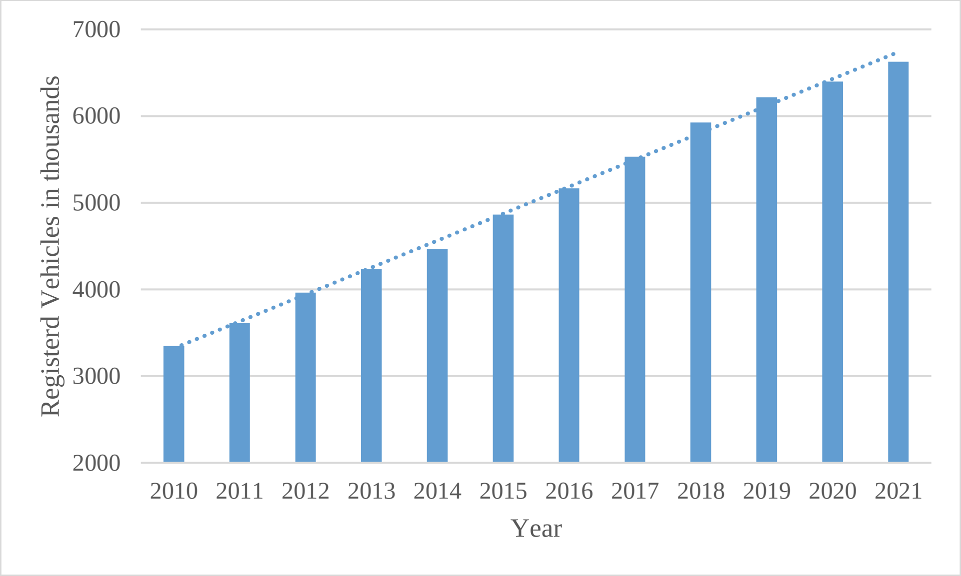

Figure 1-1: Registered Vehicles in Pakistan in Recent Years (CEIC)

1.2 Background

Pakistan is among the nations with a substantial population, exhibiting a notable trend of population growth and a concurrent rise in urbanization. The imperative for a nation's transport infrastructure to align with its developmental trajectory and accommodate burgeoning growth and demand is paramount, as it assumes a pivotal role in fostering comprehensive economic progress. Regrettably, the existing transport infrastructure in Pakistan encounters numerous obstacles, encompassing inadequate provision of public transport, absence of lane adherence, and pervasive traffic congestion.

The proliferation of private vehicles on roadways is a significant factor contributing to traffic congestion in Pakistan. The preference for private vehicles over public transport among the majority of citizens in the country can be attributed to the unsanitary conditions and inadequate capacity of the latter. Consequently, there is a daily escalation in the volume of traffic, leading to prolonged delays and heightened frustration among both drivers and passengers.

In order to tackle this issue, it is imperative to devise and execute efficient traffic management strategies, specifically focusing on signalized intersections where congestion is most pronounced. The management of traffic in Pakistan is further complicated by the absence of compliance with traffic regulations and lane etiquette, particularly among individuals from the lower-middle-class and those residing below the poverty threshold, who frequently rely on motorcycles for their daily transportation needs.

The saturation headway is a significant metric used to assess the traffic flow and capacity of roadways, and it is closely linked to the saturation flow rate. The parameter in question holds significant importance within the field of traffic engineering, as it plays a crucial role in the design and optimization processes of signalized intersections and roundabouts. Nevertheless, the determination of saturation headway is a complex task owing to the inherent variability in traffic flow and the diverse composition of vehicle types. Furthermore, the saturation headway is subject to the influence of various factors such as traffic volume, vehicle speeds, and driver behavior, which renders its accurate estimation a complex task. Hence, it is imperative to conduct additional research in order to enhance the precision and dependability of techniques employed for estimating saturation headway in diverse traffic scenarios, encompassing heterogeneous traffic conditions prevalent in Pakistan.

In order to effectively tackle these challenges, it is imperative to formulate novel models for saturation flow rate that are grounded in regional norms, while simultaneously assessing the capacity and quality of service of signalized intersections in Pakistan. Furthermore, it is imperative to collect precise data utilizing appropriate methodologies for determining saturation flow rates and identifying appropriate research locations, specifically focusing on major intersections characterized by substantial traffic volumes.

In summary, traffic congestion poses a significant challenge in Pakistan, particularly in urban regions characterized by rapid population growth and inadequate transport infrastructure to meet the escalating demand. There is a pressing need for the implementation of efficient traffic management strategies, specifically focusing on signalized intersections, in order to enhance traffic flow and mitigate delays. Nevertheless, the complexities associated with traffic management in Pakistan, such as the heterogeneous composition of traffic and the prevalent non-compliance with traffic regulations, underscore the necessity of formulating novel saturation flow models that align with regional norms. Additionally, it is imperative to collect precise data employing appropriate methodologies in order to address this issue effectively.

1.3 Scope and Research Objective

The determination of the level of service at signalized intersections relies heavily on the saturation flow rate (SFR), which is a crucial parameter. The term "capacity" pertains to the upper limit of vehicle flow that can traverse a lane without interruption within a given time interval. The determination of the SFR relies on a crucial factor known as the Passenger Car Unit (PCU), (Radhakrishnan, 2011) which takes into account the relative weighting of various vehicle categories within the traffic flow. Nevertheless, the task of determining Passenger Car Units (PCUs) in heterogeneous traffic poses significant challenges. Hence, the necessity for precise calibration of SFR that is specific to the region becomes crucial, especially in developing nations like Pakistan, where there is a significant presence of traffic heterogeneity, (Preethi P. , 2019). The Highway Capacity Manual (HCM-2000) offers a standardized SFR of 1900 pcu/h/ln, which can be modified according to various factors including lane width, presence of heavy vehicles, pedestrians, and intersection design characteristics. Nevertheless, it is important to note that these modifications might not sufficiently capture the traffic conditions prevalent in developing nations.

Another crucial factor to consider is the saturation headway, which refers to the temporal gap between consecutive vehicles in high traffic situations (Eri Aoyama, 2020), (Abuhamda, 2015). Determining the aggregate capacity of an intersection and guaranteeing efficient traffic movement are of utmost importance. Determining the saturation headway with precision can present difficulties, especially in traffic scenarios characterized by heterogeneity, as distinct vehicle categories exhibit diverse temporal intervals between them. Hence, the establishment of a saturation headway that is tailored to the specific region becomes imperative in order to optimize traffic control and enhance the quality of service at signalized intersections.

The objective of this study is to establish a saturation flow rate at signalized intersections in Faisalabad, Pakistan, within the framework of considering traffic heterogeneity and regional norms. The research will entail conducting on-site measurements of traffic flow and vehicle attributes across various types of intersections. Multiple factors will be considered, including lane width, presence of heavy vehicles, and design elements of the intersections, (Shao, 2011). The findings of this study will provide valuable insights for transportation planners and policymakers in making well-informed choices regarding the design and administration of signalized intersections. Ultimately, these decisions will contribute to the advancement of a transportation system in Faisalabad, Pakistan that is both more efficient and sustainable.

1.4 Relevance to National Needs

The determination of the saturation flow rate holds significant significance within the domains of traffic engineering and urban planning, particularly in the context of fulfilling Pakistan's national needs. The urban regions of Pakistan are presently seeing notable difficulties with the increasing traffic congestion, leading to extended travel durations, heightened fuel consumption, and amplified environmental pollution. By conducting a meticulous assessment of the saturation flow rate, authorities has the capability to modify traffic signal timings and intersection designs with the aim of optimizing the effectiveness of traffic flow.

Moreover, considering the continuous urbanization process in Pakistan, it is crucial for the country to give priority to the enhancement of its road infrastructure to adequately address the needs of its growing population. The measurement of the saturation flow rate allows urban planners and transportation engineers to optimize the design of roads, intersections, and public transportation systems to efficiently accommodate the projected traffic volume.

Furthermore, it is crucial to consider the economic implications linked to the saturation flow rate. The precise measurement of the saturation flow rate is of utmost importance in facilitating effective traffic control, thus reducing the adverse economic impacts associated with traffic congestion, such as wasted time and heightened fuel costs. As a result, it is plausible that this could lead to an improvement in productivity and a stimulation of economic growth.

The saturation flow rate is a significant metric that directly influences the optimisation of traffic, development of infrastructure, economic well-being, and environmental sustainability within the specific context of Pakistan's national needs. The incorporation of this notion into transportation planning and policymaking holds the potential to augment the effectiveness and robustness of urban centers, while concurrently addressing the pressing challenges posed by urban congestion and expansion.

1.5 Thesis Organization

Chapter 1: Introduction, Scope, and Objectives.

This chapter provides a discussion on the research issue and highlights the significance of the study. The study's scope and objectives are delineated, with the formulation of research questions and hypotheses. The examination of the study issue's significance is conducted regarding its applicability within the discipline of transportation engineering and its potential to enhance traffic flow in urban environments.

Chapter 2: Literature Review on Saturation Flow Rate.

This chapter provides a comprehensive assessment of the existing literature pertaining to saturation flow rate and the various factors that influence it. The determination of the saturation flow rate involves an examination of the passenger car unit and saturation headway ideas. The literature review encompasses an examination of several field measurement techniques, as well as models and approaches employed for the estimation of saturation flow rate, including the utilization of the Highway Capacity Manual.

Chapter 3: Methodology of the Study.

This chapter provides a comprehensive explanation of the research methodology and design. The study encompasses an examination of the designated region, the techniques employed for data collection, and the methodologies employed for data analysis. The process portion of the study also provides a description of the sample plan and the criteria employed to choose the study intersections.

Chapter 4: Data Analysis.

This chapter explores the analysis of vehicular data, specifically focusing on the extraction of data from videos and the subsequent techniques for sorting and organizing this data.

Chapter 5: Calculation and Discussion of Results.

This chapter centers on the detailed procedure of determining the saturation flow rate, involving a thorough analysis of the gathered data. Following this, a thorough examination of the collected data is conducted, hence facilitating a detailed discourse on the results. The approach provides a comprehensive analysis of the complex dynamics involved in determining the saturation flow rate. This contributes to the advancement of our knowledge in this field and provides significant insights into the potential consequences and applications of this determination.

Chapter 6: Conclusion and Recommendations.

The last section of the study provides a concise overview of the key findings, while also revisiting the research questions and assumptions. The study's findings are presented, and the practical ramifications as well as potential avenues for further research are examined. This study offers recommendations for enhancing traffic flow within the designated area, as well as suggestions for further research pertaining to the saturation flow rate.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction to Saturation Flow Rate

The Federal Highway Administration (FHWA) defines saturation flow rate as *"the equivalent hourly rate at which vehicles can traverse an intersection approach under prevailing conditions, assuming a constant green indication at all times and no loss time, in vehicles per hour or vehicles per hour per lane."*

The proliferation of urbanization and mobility in developing nations has led to a gradual rise in the quantity of automobiles, leading to regular occurrences of traffic congestion, especially at junctions where vehicular and pedestrian traffic intersect. Engineers have endeavored to enhance intersection capacity by implementing refined signal timing and design strategies as a means to mitigate this issue. The analysis of capacity is of utmost importance in engineering applications, particularly in the context of signalized crossings where the assessment of capacity relies heavily on the saturation flow rate (SFR).

Direct measurement of traffic flow is not feasible for traffic engineers, necessitating the use of estimation techniques. The determination of the saturation flow rate is influenced by various aspects, including the composition of traffic, geometric limitations, and the presence of pedestrians. Consequently, it becomes imperative to employ diverse methodologies to accurately calculate the SFR. The U.S. Highway Capacity Manual (HCM) suggests two approaches for determining the saturated flow rate: the adjustment method and the field measurement method.

The adjustment technique is a mathematical formula involving the base saturation flow rate (BSFR) and adjustment factors, which are used to modify or refine the calculation. The term "BSFR" denotes the saturation flow rate in optimal circumstances for each element that influences it, whereas adjustment factors pertain to the extent of impact exerted by several factors on the saturation flow rate. The saturation flow rate is determined using the field measurement approach, which involves calculating the reciprocal of the saturation headway. The saturation headway refers to the average headway between the fourth and last vehicle in the line. The determination of the saturation flow rate is highly dependent on the saturation headway, which is defined as the time gap between cars starting from the fourth or fifth vehicle in the queue until the last vehicle has completely cleared the intersection.

The heterogeneity index (HI) is employed to account for the diversity in traffic by comparing a specific attribute in a dimensionless manner. The purpose of this index is to determine the passenger car equivalent by standardizing all vehicle types into a singular unit of measurement. The Equivalency factor is utilized to determine the number of passenger car units based on the specific intersection and traffic patterns. The utilization of PCUs plays a crucial role in mitigating the volume of cars traversing an intersection, hence effectively mitigating congestion.

In the context of emerging nations such as Pakistan, where there is a significant diversity in road traffic, it becomes imperative to comprehend essential traffic flow attributes, such as traffic volume, to effectively strategize, construct, and manage roadway systems. There are two methods available for determining the required saturation flow to ascertain the capacity of an intersection. The initial approach entails conducting on-site investigations to assess the saturation flows at the specific intersection or intersections under consideration. In contrast, the second approach relies on utilizing "base saturation flow values," which encompass theoretical maximum values. The basic flow rates can be adjusted to account for the operational and physical characteristics of junctions, as well as the methodologies used in intersection capacity analyses. Accurate determination of an intersection's capacity necessitates the careful consideration of mathematical correlations between saturation flows and the physical and operational aspects of signalized crossings.

2.1.1 Impact of Saturation Flow Rate

The saturation flow is the maximum vehicle capacity at a specific point during a green signal phase of a traffic signal. This metric has a significant impact on the dynamics of traffic flow and the overall functionality of transportation systems. Increasing the saturation flow rate has several benefits for traffic flow, including improved efficiency, reduced congestion, and enhanced vehicle movement. The capacity of intersections is directly related to the saturation flow rate. A higher saturation flow rate leads to increased intersection capacity and greater vehicular throughput within a given time (Ghanim, 2022). The synchronization of traffic signal timing depends on this rate, enabling engineers to accurately determine the optimal durations for green signals at various stages of the traffic signal cycle. The objective of this endeavor is to optimise the movement of vehicles and minimise instances of congestion.

The saturation flow rate has a notable impact on queue lengths at intersections. Higher rates can effectively minimise queue elongation during periods of heavy traffic. The concept is closely related to the level of service (LOS) in transportation engineering (Teply, 1991). Higher saturation flow rates are associated with improved traffic conditions and reduced congestion. The intricate relationship among these factors has substantial effects on travel duration, congestion, and economic considerations. Efficient traffic flow has a substantial impact on the economy as it reduces fuel consumption, emissions, and enhances productivity for businesses reliant on transportation networks.

2.2 Saturation Flow Rate

The saturation flow rate is a fundamental metric utilized for evaluating the efficiency of traffic flow at signalized crossings. The term "it" refers to the maximum capacity of cars that can traverse an intersection approach lane within a one-hour time during the green phase.

The determination of optimal cycle time and green interval duration for an intersection's efficient operation is heavily reliant on the saturation flow rate's significance. A marginal alteration in the saturation flow rate can have a substantial impact on these metrics, thereby influencing the capacity analysis of the intersection.

Saturation flow rate is defined differently across several countries, although adhering to a common underlying principle. The saturation flow rate in the United States is formally defined as the rate at which vehicles pass through a lane per hour, per lane (vphpl), under the assumption that the green phase is consistently accessible to the approaching cars. The expression of saturation flow rate differs between Canada and Australia. In Canada, it is denoted as passenger-car units per hour of green (pcu/hr green), but in Australia, it is denoted as through-car units per hour (tcu/hr) (Teply, 1991).

It is imperative to acknowledge that the notion of saturation flow rate operates on the assumption that, upon the signal transitioning to green, traffic is discharged at a consistent pace until either the queue is completely depleted, or the green period concludes. The rate of departure from a traffic intersection may exhibit a decrease in the initial few seconds as vehicles gradually accelerate to attain their regular operating speed. Similarly, there may be a decrease in departure rate during the period following the conclusion of the green interval, as the volume of vehicles diminishes.

In the realm of signalized intersections, the saturation flow rate is an essential element that significantly impacts both the effective functioning and capacity assessment.

2.2.1 Measurement Techniques

The evaluation of the optimal rate of traffic flow at signalized crossings relies heavily on the measurement of saturation flow rate. Various techniques can be employed to quantify the saturation flow rate, which can be classified into three distinct categories.

2.2.1.1 Visual Estimation

Visual Estimation is a cost-effective and straightforward method in which a trained observer, positioned on the side of the road, visually assesses the time duration between two successive vehicles using a stopwatch. (Bara' W. Al-Mistarehi, 2020)

2.2.1.2 Time-Lapse Photography

Time-lapse photography involves positioning a camera at a stationary location and configuring its shutter to capture images at regular intervals. The temporal gap between the leading edge of one vehicle and the leading edge of the subsequent vehicle can be determined by analyzing the photographs. (Bara' W. Al-Mistarehi, 2020)

2.2.1.3 Automated Sensors

Automated sensors are a highly advanced and precise methodology for quantifying saturation headway. These sensors have the capability to autonomously measure the temporal gap between two successive vehicles without human intervention. (Wang L. , 2018)

2.2.2 Factors Affecting Saturation Flow Rate.

The saturation flow rate is directly proportional to the width of the lanes. (Shao, 2011)

The design of intersections has been observed to have a correlation with saturation flow rates, with intersections featuring a greater number of lanes or dedicated turn lanes exhibiting higher saturation flow rates.

The optimization of traffic flow and the enhancement of the saturation flow rate can be achieved by the appropriate timing of traffic signals.

The saturation flow rate experiences a drop because of heightened congestion and delay when traffic volume increases.

The composition of cars present on roadways can have an impact on the saturation flow rate, since the presence of larger or slower vehicles has the potential to diminish the total capacity of the transportation system.

The saturation flow rate can be influenced by various aspects of driver behavior, such as their velocity and response time.

The saturation flow rate may be negatively impacted by adverse weather conditions, such as heavy rain or snow, which can lead to lower visibility and impaired vehicle performance.

The road surface condition is deemed to be substandard. The saturation flow rate of automobiles may be diminished due to the presence of road surface problems, such as potholes or uneven pavement, which impede the speed of vehicles. (Shao, 2011)

2.2.3 Adjustments of Saturation Flow Rate.

The determination of saturation flow rate encompasses the analysis of many parameters that exert influence on the flow of cars within a specific lane group. Typically, adjustment factors are employed to modify the optimal saturation flow rate to consider the impact of various roadway attributes, vehicle composition, turning proportions, and additional variables. According to the U.S. Highway Capacity Manual (HCM) in 1994, the optimal saturation flow rate is 1,900 passenger cars per hour of green time per lane (pcphgpl). The calculation for determining the saturation flow rate of a signalized intersection approach is provided in the U.S. Highway Capacity Manual (1994).

$$S = S0 \times N \times fHV \times fw \times fg \times fp \times fbb \times fa \times fLT \times fRT$$

where:

S = Saturation flow rate under prevailing conditions, expressed in vehicle per hour of effective green time

N = Number of lanes in the lane group

fHV = Adjustment factor for heavy vehicles (any vehicle having more than four tires touching the pavement)

fw = Adjustment factor for lane width

fg = Adjustment factor for approach grade

fp = Adjustment factor for the existence of parking activities in a parking lane

fbb = Adjustment factor for the blocking effect of local buses stopping within the intersection area

fa = Adjustment factor for area type

fRT = Adjustment factor for right turns in the lane group

fLT = Adjustment factor for left turns in the lane group

However, the procedure for estimating saturation flow rate in the HCM (2000) is slightly different from that of the U.S. HCM (1994). In the HCM (2000), the lane utilization factor, fLU, was included in the saturation flow prediction formula. In addition, pedestrian-bicycle blockages in both the left-turn and right-turn adjustment factors were separated into two distinct factors: pedestrian-bicycle adjustment factor for left-turn movements, fLpb, and pedestrian-bicycle adjustment factor for right-turn movements, fRpb (HCM, 2000).

2.3 Headway

The concept of headway refers to the time interval or duration between the leading edge of one motor vehicle and the leading edge of the subsequent motor vehicle on a certain road or highway. The notion holds significant importance in the field of traffic engineering and management, as it exerts a direct influence on both the capacity and safety of roadways.

The rate of progress can be influenced by a multitude of aspects, encompassing the velocity of the cars, the quantity of vehicles present on the roadway, the conduct of drivers, the state of the road, and the prevailing weather circumstances. A reduced headway interval corresponds to a decreased distance between cars, hence potentially enhancing traffic throughput while concurrently elevating the likelihood of collisions. On the other hand, a greater distance between vehicles, indicated by a longer headway, results in decreased traffic flow but perhaps enhanced safety.

2.3.1 Saturation Headway

The concept of saturation headway is an often-employed phrase within the field of traffic engineering, serving to delineate the minimal temporal gap necessary between two vehicles to attain the utmost capacity of vehicular movement on a given roadway or highway. The term "minimum time headway" refers to the lowest duration between two successive vehicles that allows for the optimal utilization of the roadway's capacity.

2.4 Passenger Car Equivalent

The Passenger Car Equivalent (PCE) is a fundamental concept within the field of transportation engineering, serving as a valuable tool for assessing and comparing the capacity of different vehicle types operating on a given transportation network. Accurate evaluation of the influence that various vehicles exert on the transportation network is a crucial task for transportation planners and engineers, as it enables the development of efficient and effective transportation infrastructure. The Passenger Car Equivalent (PCE) is a metric used to facilitate the comparison of different vehicles by standardizing their capacity in relation to passenger cars. This metric takes into account multiple variables that impact the capability of a vehicle, encompassing dimensions, mass, and velocity.

PCE values have been computed for a diverse array of vehicles, encompassing passenger cars, buses, lorries, and bicycles. As an illustration, the passenger car's Passenger Car Equivalent (PCE) is commonly one, whereas a heavy-duty truck often possesses a PCE value of three or greater. The PCE, is a crucial instrument for assessing transportation initiatives, including but not limited to bus rapid transit (BRT) systems, bike lanes, and other environmentally friendly means of transportation. The utilization of the PCE enables planners to proficiently achieve equilibrium among the diverse requirements of distinct road users, including pedestrians, automobiles, and heavy-duty vehicles. In addition, the PCE assists policymakers in formulating appropriate infrastructure plans, allocating resources efficiently, and optimizing the flow of traffic. (Ghanim, 2022)

2.5 Saturation Flow Rate - A Review of Past Research

(Abuhamda, 2015) employed the base saturation flow rate. The Highway Capacity Manual (HCM) suggests a base saturation flow rate of 1,900 passenger cars per hour per lane (pc/h/ln). Nevertheless, the value of this variable is not universally consistent and can vary across cities because of disparities in local driver conduct and traffic circumstances. The objective of this study was to determine the base saturation flow rate in Doha, Qatar. To accomplish this goal, the researchers collected data from a total of 1,431 vehicles that were passing through three signalized intersections. These vehicles were organized into 86 queues. The study found that the average saturation headway was 1.55 seconds, which led to a base saturation flow rate of 2,323 pc/h/ln.

In a study conducted by (Arasan, 2006) in 2006, The saturation flow rate per unit width of approach shows a slight increase with increasing approach width. The saturation flow rate per meter width increases as the approach width increases due to the improved utilization of road space by heterogeneous traffic vehicles. As road width increases, vehicles of different sizes can more effectively utilize the available space, especially when traffic is heavy.

(Bara' W. Al-Mistarehi, 2020), studied factors influencing the saturation flow rate (SFR) for different turning maneuvers at signalized intersections in Jordan. The investigation involved conducting site visits to specific locations, utilizing video camera technology to enhance the process. The data collection process adhered to the prescribed procedures specified in the Highway Capacity Manual. This study aimed to investigate the factors influencing the saturation flow rate (SFR) in signalized intersections in Jordan. The findings of this study will enhance our understanding of traffic dynamics in this context.

(Rahman, 2005), presents an alternative methodology for calculating the saturation flow rates at signalized crossings, which deviates from the methodology described in the Highway Capacity Manual (HCM). This comparison analysis demonstrates that the HCM process tends to overstate the saturation flow rates for the observed junction approaches. In few instances, the observed value for this parameter reaches a maximum of 4.4%.

(Wang L. , 2018) highlighted that the utilization of video detector data can yield headway measurements; nevertheless, it is crucial to implement a filtering process to eliminate aberrant data points in order to enhance the accuracy of the estimation. The paper introduces an iterative strategy that relies on quantiles to effectively eliminate anomalous data points while also preserving a significant degree of flexibility. The estimation accuracy of the SFR is influenced by both the selection of quantiles and the duration of the data. It is recommended to utilise the 80th percentile as the quantile measure and to ensure that the duration of the data is at least 150 minutes.

(Liu C.-q. S.-m., 2012) found that conventional approaches, which mostly rely on calculating the average value of recorded queue discharge headways to estimate the saturation headway, may result in an underestimation of the saturation flow rate. Research indicates that the mean value of queue discharge headways is higher than the median value, and there is a positive skewness observed in the distribution of headways.

(Mathew, 2021), Studied the presence of many types of vehicles, each with unique static and dynamic characteristics, has an impact on traffic dynamics. This combination results in traffic phenomena characterised by non-uniform lane utilisation and intricate vehicle-following behaviours. As a result, the rate at which queues are discharged during green signals displays unpredictability, which presents difficulties in determining a prolonged and consistent phase of queue discharge that is crucial for estimating saturation flow. The present study is based on the notion that the variations in discharge, which are ascribed to the existence of diverse vehicle types, can be clarified by employing the concept of Passenger Car Units (PCUs). This work presents a unique model that is introduced to forecast saturation flow, taking into account PCU considerations, which is obtained directly from empirical field data.

(Afzal Ahmed, 2020), Found that the examination of temporal dynamics inside green time reveals that the traffic flow during this period is non-uniform. The findings of the study revealed an unexpected trend: during the initial moments of the green signal, there is a notable increase in traffic flow compared to the subsequent duration of the green signal. This observation contradicts the commonly held belief that traffic flow is lower during the initial seconds due to vehicles accelerating. The irregularity in the traffic count per second can be explained to the presence of motorcycles positioned at the forefront of the queue.

(Radhakrishnan, 2011)Highlighted that the Highway Capacity Manual (HCM) suggests the use of a saturation flow model primarily in scenarios where conditions are homogeneous, and it has limited capacity to account for variation. However, the traffic conditions in many regions across the globe exhibit significant heterogeneity, making it difficult to establish a universally applicable definition for saturation flow. The utilization of passenger car units (PCUs) is essential due to the diversity in vehicle types.

(Iqbal M J, 2011), The study involved the collection of data using the video recording method at eight distinct intersections located along Shahra-e-Faisal, a prominent arterial road in Karachi, Pakistan. The films that were recorded were subsequently viewed in the laboratory on a sizable screen, and the necessary data was extracted. The calculation of Passenger Car Unit (PCU) values was performed via regression techniques. The focus of the study was centered on Karachi, the largest city in Pakistan. The present study involved the calculation of PCU values for several types of automobiles, which were found to differ from the values previously established by countries such as Great Britain, the United States, and Australia.

CHAPTER 3: RESEARCH DESIGN & METHODOLOGY

3.1 Introduction

The study's methodology centered on the estimation of the saturation flow rate, with particular emphasis placed on the significance of saturation headway. The determination of the pace at which vehicles traverse an intersection during periods of high demand is a crucial factor in the planning and design of traffic engineering systems. The saturation flow rate is a quantifiable measure that represents the highest possible rate of vehicle flow that can be sustained at an intersection while maintaining an acceptable level of service. The saturation headway, which is the lowest uninterrupted time required for a vehicle to traverse an intersection, directly influences its performance.

Methodology: -

Selection of Signalized Intersection: The initial stage of the process entailed the identification and selection of an appropriate signalized intersection. This selection was made by considering many factors such as the level of traffic flow, the design of the intersection, the presence of clearly marked lanes, and the absence of congestion.

Data Collection: A video recorder was employed to document the flow of traffic during periods of high congestion, and subsequently, the data was manually tallied. The data that was gathered encompassed the count of vehicles traversing the intersection, their respective classifications, as well as the precise timestamps of their arrival and departure. To mitigate potential inaccuracies in headway calculations, the research team opted to disregard brief queue interruptions during the data collection process.

Headway Calculation: The saturation headway was calculated by doing multiple visual assessments and attentively observing the time intervals between vehicles. The method employed in this study involved the calculation of the duration of uninterrupted vehicle traffic at the intersection during peak hours. (Abuhamda, 2015)

Saturation Flow Rate Calculation: The saturation flow rate was determined by dividing 3600 to the average headway which is carefully calculated after taking PCUs per cycle and the corresponding saturation time, also taking into account the number of observed lanes.

Data Analysis: The data that was gathered was subjected to analysis in order to ascertain the saturation flow rate for each category of vehicles, encompassing passenger cars, buses, motorcyclists, and large vehicles.

Verification: Ultimately, the findings were corroborated through a comprehensive analysis, which involved a thorough examination of the available literature pertaining to saturation flow rates and saturation headways across different vehicle categories.

In general, the methodology placed emphasis on the significance of saturation headway when determining the saturation flow rate, given its direct impact on the intersection's capacity and level of service. The utilization of saturation headway has the potential to yield more precise outcomes and facilitate the development of traffic control strategies aimed at enhancing traffic flow. The flowchart of the research methodology is illustrated in **Figure 3-1** and **Figure 3-2. Figure 3-1** shows the overall research methodology structure adopted while **Figure 3-2** shows the methodology adopted for precisely finding the saturation flow rate. The following sections of this chapter go into more detail about each stage of the research process.

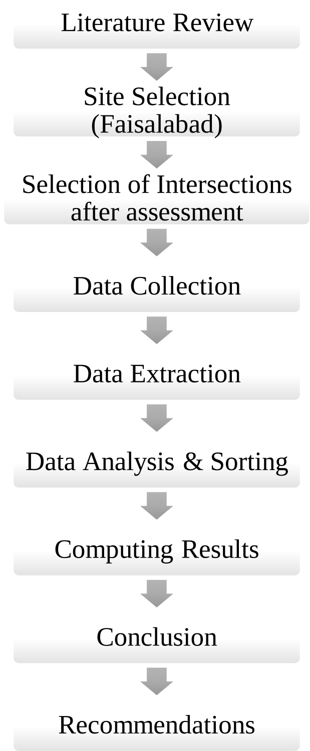

Figure 3-1: Research workflow

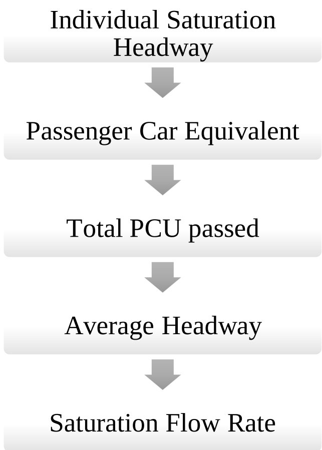

Figure 3-2: Saturation Flow Rate Methodology

3.2 Defining Research Area

Faisalabad, located in Pakistan, is a city characterized by its vibrant atmosphere and notable population growth. The urban area exhibits a population density over 6300 individuals per square mile, positioning it among the cities with the highest population densities in Pakistan. Owing to its prominent position as a notable center for textiles and industrial activities, Faisalabad garners the attention of enterprises and individuals from adjacent districts such as Jhang, Toba Tek Singh, and Chiniot. The increase in population and economic activity has led to notable transport issues, namely at critical junctions across the urban area.

In recent years, the issue of traffic congestion in Faisalabad has emerged as a prominent concern, leading to prolonged delays that elicit feelings of irritation and tension among commuters. The escalation of gasoline costs resulting from global inflation has exacerbated the issue, as individuals want to expedite their journeys to their desired destinations. The urban business sector elicits diverse traffic patterns, drawing in inhabitants from various social strata.

A noteworthy characteristic of the chosen crossroads is the lack of proximate bus terminals or curbside parking facilities. In addition, the presence of non-motorized vehicles on the roads is minimal. The crossings that have been chosen to exhibit pre-timed signal characteristics and demonstrate a lack of pedestrian presence. These characteristics render the intersections conducive for investigating the impacts of traffic flow in a homogeneous setting.

To gather data during periods of high demand, the researcher employed videographic methodology. The methodology employed in this study entailed the utilization of a video camera to capture and document the traffic patterns occurring at the designated intersections. Subsequently, the movies were subjected to a thorough inspection, and the data were meticulously tallied by manual means, with a specific focus on lengthier lineups that were devoid of any congestion. Subsequently, the gathered data was systematically arranged in a suitable manner to facilitate analysis.

In conclusion, Faisalabad is an emerging urban center characterized by a vibrant commercial sector that appeals to individuals from many socioeconomic strata. Nevertheless, the expansion has resulted in notable traffic issues, specifically at crucial junctions.

3.3 Study Area – Urban Major Intersections

The chosen intersections include certain characteristics that render them suitable for investigating the impacts of traffic flow in heterogeneous circumstances. These features include the lack of bus stations and side-of-the-road parking, the absence of non-motorized vehicles, the implementation of pre-timed signals, and a limited presence of pedestrian activity. The videographic methodology was employed to gather data during periods of high traffic for the purpose of analysis.

Railway Square provides convenient access to the entirety of the urban area. In the morning, individuals residing primarily in the northern vicinity of the square relocate to the business district, while in the evening, they return to their respective residences. This pattern is attributed to the concentration of residential population residing north of the square, juxtaposed with the centralization of business activities on the southern side.

Figure 3-3: Aerial View of Railway Square

Chenab Square benefits from its convenient proximity to both the Government College University and the Central Business District. The transportation infrastructure facilitates connectivity between the urban center and the Faisalabad International Airport, in addition to serving the residential localities of District Jhang and District Toba Tek Singh. Located opposite the Square are significant educational establishments.

Figure 3-4: Aerial View of Chenab Square

Stadium Square serves as a central hub connecting traffic from neighboring tehsils, motorways, and other residential projects. Additionally, this infrastructure connects the city to the fourth-largest hospital in the Punjab region. The use of the square encompasses official, recreational, and educational purposes for multiple adjacent residential structures.

Figure 3-5 Aerial View of Stadium Square

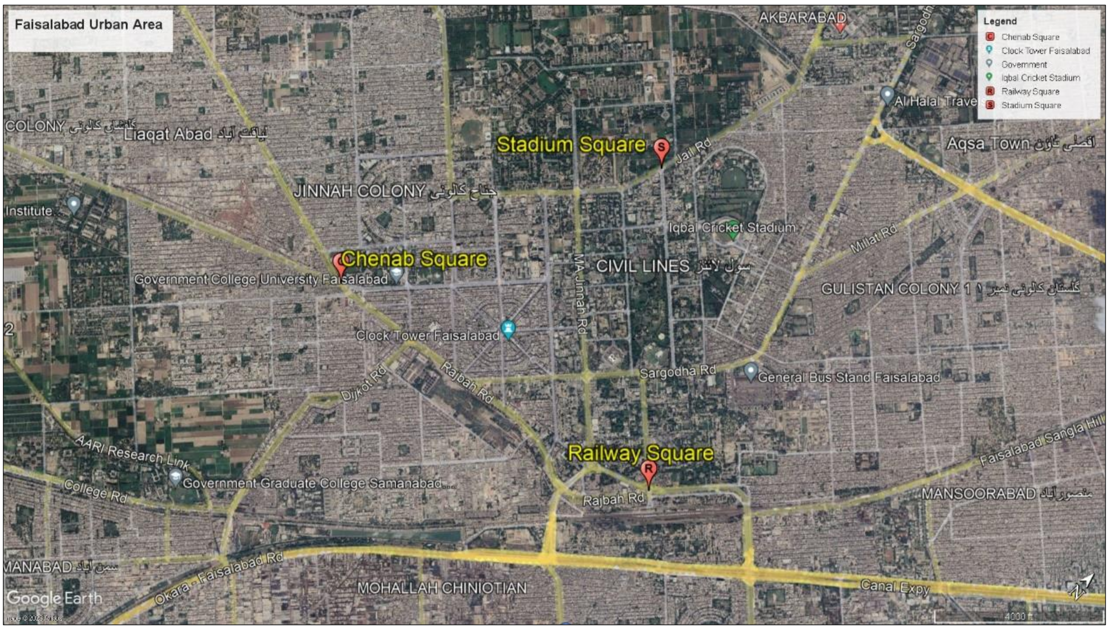

Figure 3-6 Faisalabad Urban Area with marked studied intersections

3.4 Data Collection

The objective of our study was to ascertain the saturation flow rate at signalized crossings in Faisalabad. These intersections were chosen based on their propensity for experiencing extended waits during peak periods. The intersections are equipped with several lanes, and data was gathered from each lane at these intersections during the peak hours of weekdays (specifically, from 07:00 to 09:00 and 17:00 to 19:00). It is important to note that the data collection took place while there were no instances of traffic congestion in the downstream flow direction.

To ensure the collection of precise data, we strategically positioned two video cameras at each intersection, selecting a height that would minimise any potential obstructions and guarantee clear and unobstructed recording. The selection of video camera placements was made following careful consideration and extensive on-site observations. Furthermore, the acquisition of requisite permits was undertaken from the proprietors of diverse structures and establishments. (Bara' W. Al-Mistarehi, 2020)

During the process of data collecting, we encountered various problems. These challenges included the absence of controlled lane flow, the presence of smaller vehicles such as two-wheelers and three-wheelers maneuvering through gaps between larger cars and positioning themselves at the front of the queue, as well as the unpredictable movement of vehicles during green signals. To tackle these issues, we strategically deployed cameras at a specific location to observe the flow of traffic at the intersection. This enabled us to precisely monitor the passage of each vehicle and accurately calculate the time intervals between them, known as headway values.

Furthermore, with the videography, we conducted data collection of geometric attributes at each designated intersection. This encompassed the quantification of several factors such as the number of lanes, lane width, gradient, and the distribution of right and left turns.

The strategic placement of cameras was crucial in facilitating our data collection procedure since it enabled precise monitoring of the trajectory of every vehicle as it traversed the intersection. The sites for the cameras were meticulously chosen following comprehensive on-site investigations, with the aim of ensuring unobstructed views and optimal recording clarity. This facilitated the acquisition of high-quality data that precisely depicted the traffic patterns at every intersection.

Table 3-1: Geometric Data of Intersection Studied

Sr #	Name of Road	Inter-section	No. of Marked Lanes	No. of Observed Lanes	Intersec-tion Type	Nature of Road	Type of Flow	Width (Ft)
1	Jhang Road	Chenab Square	3	5	Four Legged	Divided	One Way	33
2	Jail Road	Stadium Square	3	4	Three Legged	Divided	One Way	30
3	Abdullahpur Overpass Road	Railway Square	5	7	Four Legged	Divided	One Way	60

Table 3-2 Signal time collected during analysis.

Intersection	Signal Duration	Time (Sec)
Chenab Square	Available Green Time	25
	Amber	3
	Cycle Length	102
Stadium Square	Available Green Time	40
	Amber	3
	Cycle Length	95
Railway Square	Available Green Time	43
	Amber	3
	Cycle Length	130

Table 3-3 Attributes During Data Collection

Data Attributes	
Lane Configuration	Vehicle Types
Traffic Signal Timings	Flow Variation
Driver Behavior	Traffic Density
Road Geometry	Pedestrian and Bicycle Movements
Data Collection Duration	Weather condition
Roadside Distractions and Obstructions	Driver Compliance
Day	Weekday/Weekend
Time	Peak Hour

Figure 3-7 Snapshots of videography at various intersections

Figure 3-8 Sample images of vehicle types   (Google Images, 2023)

CHAPTER 4: DATA ANALYSIS

This chapter undertakes a comprehensive examination of three particular junctions through an in-depth analysis of data. The aforementioned intersections hold great significance in our research, as they provide substantial contributions to our comprehension of the intricate dynamics of urban traffic. By employing rigorous data collection methods, we have acquired a comprehensive dataset that serves as the foundation for our analytical endeavors. The main objective of this data-driven investigation is twofold: to gain a comprehensive understanding of existing traffic patterns and to establish a solid foundation for making well-informed decisions in the fields of traffic management and urban planning. Through the examination and interpretation of factual data pertaining to these intersections, our research efforts make a valuable contribution to the advancement of intelligent transport systems and the overarching objective of improving urban mobility.

4.1 Vehicular Data Analysis

The data analysis phase encompassed a rigorous scrutiny and computation of multiple factors to evaluate the traffic flow and intersection capacity at the intersections under study in Faisalabad. The initial procedure involved the computation of the aggregate Passenger Car Units (PCUs) by adding together the PCU values corresponding to each individual vehicle class. The PCU metric serves as a standardized measure of the relative capacity of various vehicle types compared to a normal passenger car, (Mondal, 2020).It offers a full assessment of both the volume and composition of traffic. This methodology ensured a comprehensive comprehension of the traffic composition at the crossings.

To conduct a more comprehensive assessment of the junctions' performance, the saturation flow rate (SFR) was calculated by dividing the aggregate count of passenger car units (PCUs) by the complete duration of the data collection period of the respective cycles after ignoring the startup time loss. By doing this computation, it was possible to evaluate the upper limit of the number of Passenger Car Units (PCUs) that could traverse the junctions during the designated time frame. The Saturation Flow Rate (SFR) is a crucial measure in the field of traffic engineering. It offers valuable information about the effectiveness and capacity of intersections, enabling educated choices regarding intersection design, traffic signal timings, and traffic management tactics.

The data analysis in this study employs the use of Passenger Car Units (PCUs) and the calculation of the Saturation Flow Rate (SFR), which conforms to established norms in the field of traffic engineering. Various studies and practical implementations have utilized comparable approaches to assess traffic performance and enhance intersection operations. The utilization of Passenger Car Units (PCUs) facilitates a comprehensive depiction of diverse vehicle categories and their respective capabilities, hence enhancing the precision in comprehending the overall traffic dynamics.

Through the utilization of this data analysis approach, which integrates the use of Passenger Car Units (PCUs) and the computation of the Saturation Flow Rate (SFR), a comprehensive comprehension of traffic flow patterns was attained. This facilitated the ability to make well-informed judgements and provide recommendations pertaining to traffic management, optimization of signal timing, and design of intersections. The approach presents a measurable parameter for evaluating the capacity and performance of intersections, hence making a significant contribution to the advancement of efficient and secure transportation networks within the examined area.

Table 4-1 Number of vehicles passing through each cycle green time at Chenab Square

Intersection		Chenab Square				
Veh. Type		2-Wheelers	3-Wheelers	Cars/Mini Van	LCV/MiniBus	Buses/Trucks
Cycle Nos.	1	32	14	5	1	1
	2	29	10	1	3	0
	3	20	9	5	4	0
	4	20	14	3	3	0
	5	17	5	1	2	0
	6	32	5	4	0	0
	7	42	11	7	2	0
	8	23	7	4	5	0
	9	34	12	7	2	0
	10	32	14	5	3	0
	11	32	16	5	2	0
	12	38	15	5	1	1
	13	36	16	4	3	1
	14	43	17	9	1	1
	15	46	16	8	2	0

Table 4-2 Number of vehicles passing through each cycle green time at Stadium Square

Intersection		Stadium Square				
Veh. Type		2-Wheelers	3-Wheelers	Cars/Mini Van	LCV/MiniBus	Buses/Trucks
Cycle Nos.	1	18	7	10	1	0
	2	32	5	10	2	0
	3	23	6	13	2	1
	4	30	3	11	0	1
	5	29	6	11	2	0
	6	27	8	5	2	0
	7	33	5	13	2	1
	8	37	7	12	1	1
	9	31	6	6	2	0
	10	48	5	21	1	0
	11	29	5	12	2	1
	12	33	6	17	2	0
	13	33	7	6	2	1
	14	46	5	10	1	1
	15	37	7	11	1	1

Table 4-3 Number of vehicles passing through each cycle green time at Railway Square

Intersection		Railway Square				
Veh. Type		2-Wheelers	3-Wheelers	Cars/Mini Van	LCV/MiniBus	Buses/Trucks
Cycle Nos.	1	57	9	24	1	1
	2	65	17	18	2	0
	3	47	12	23	8	0
	4	72	23	19	3	0
	5	66	12	24	2	1
	6	46	26	27	2	1
	7	65	23	31	2	0
	8	47	20	25	1	1
	9	54	21	23	2	0
	10	57	15	28	4	1
	11	58	18	31	5	0
	12	57	14	19	7	0
	13	65	29	24	4	1
	14	54	12	25	2	1
	15	61	21	27	2	0

4.2 Data Extraction

A comprehensive study was done in Faisalabad between October 2022 and March 2023, with the aim of monitoring various phases of three signalized crossings. The study aimed to collect vehicle traffic data, signal timing information, and geometrical data. The inclusion of an extended data collection period was imperative to consider the seasonal fluctuations in weather conditions, encompassing both dry and wet periods, within the designated study area. This approach was crucial to guarantee that the outcomes of the study accurately represented the actual traffic patterns seen in real-world scenarios.

During the periods of high traffic volume in the morning and evening, the intersections are subject to traffic congestion because of an elevated presence of tricycles and the disorderly riding behaviors exhibited by motorcyclists, (Guo, 2012), (Afzal Ahmed, 2020) (Anusha, 2013). Therefore, it was imperative to meticulously watch and analyze these stages in order to comprehend the intricacies of traffic flow and potential areas of congestion. Data extraction was conducted at each selected phase located at the stop line of the signalized junctions.

At the workplace, video recordings were obtained and afterwards examined at designated workstations to extract a range of traffic stream metrics. The entirety of the traffic was classified into five distinct categories, namely: Bicycles, Three Wheelers, Passenger Cars, Minibuses/Light Commercial Vehicles, and Buses/Trucks. The categorization of vehicles was determined by considering both their static and dynamic features, resulting in a thorough depiction of the composition of traffic. Insights into the distribution of vehicle types were obtained by determining the volume of traffic and the proportional share of each vehicle class at each research section through the process of conducting manual counts of classified cars.

In order to examine the dynamics of traffic flow at intersections, a series of manual measurements were conducted. These measurements encompassed several factors such as the number of lanes, queue length, and the effective number of lanes seen during different signal phases. The measurement of the duration of the green period was conducted by employing visual signals, while ensuring precise timing of the signal intervals by the utilization of a digital stopwatch. During the red phase, an observation was made of cars that came to a complete stop at the signal, and their passing times were recorded using a stopwatch. The aforementioned observations played a pivotal role in subsequent computations pertaining to the saturation flow rate.

In general, the research utilized rigorous techniques for gathering data, including thorough data collection procedures, extended durations of observation, precise categorization of vehicle kinds, and comprehensive assessments of signal timings and traffic factors. The objective of these endeavors was to establish a strong basis for examining the dynamics of traffic flow and establishing the saturation flow rate at the intersections under study in Faisalabad.

4.3 Data Sorting

The study involved the individual examination of cycles at each intersection, with just the relevant cycles being taken into account while disregarding the cycles deemed superfluous. Reliable data for each intersection was collected through the use of field readings and video recordings, with the purpose of calculating the saturation headway. It is imperative to bear in mind that every intersection possesses unique characteristics that result in little variations in saturation headways. The Headway Method was employed to determine the passenger car equivalent (PCE), and it is seen that these variances do not have a substantial impact on the PCE.

The saturation flow rates were calculated using a comprehensive methodology. The quantity of automobiles present in the traffic flow was carefully enumerated, taking into account solely those that were positioned in the queue of vehicles at the moment the traffic signal transitioned to the green phase. The saturation flow rates were accurately determined by measuring the duration it took for the vehicles to traverse the crossings using a stopwatch.

The comprehensive technique employed facilitated a thorough examination of every junction, taking into account its distinct dynamics. The enhancement of data accuracy for saturation headways and saturation flow rates was achieved by the utilization of a combination of field readings and video recordings. This comprehensive study provides a solid basis for understanding the traffic conditions and enables effective intersection planning and management.

CHAPTER 5: RESULTS AND DISCUSSIONS

The subsequent chapter entails the presentation of the findings derived from our investigation pertaining to the saturation flow rate. The present study compares these findings with prior research conducted on the saturation flow rate in traffic conditions characterized by heterogeneity.

In addition, we employed repeated readings in order to enhance the precision of our findings. The utilization of a worksheet was employed to facilitate the categorization of different types of cars and enhance the precision of the counting procedure. Notwithstanding the constraints inherent in our study, our research outcomes serve to enhance comprehension of traffic dynamics in various traffic scenarios and can facilitate the formulation of more efficacious traffic management strategies.

5.1 Saturation Headway

The subsequent chapter entails the presentation of the findings derived from our investigation pertaining to the saturation flow rate. The present study compares these findings with prior research conducted on the saturation flow rate in traffic conditions characterized by heterogeneity.

In addition, we employed repeated readings in order to enhance the precision of our findings. The utilization of a worksheet was employed to facilitate the categorization of different types of cars and enhance the precision of the counting procedure. Notwithstanding the constraints inherent in our study, our research outcomes serve to enhance comprehension of traffic dynamics in various traffic scenarios and can facilitate the formulation of more efficacious traffic management strategies.

Table 5-1 Saturation Headway of Vehicle type at Intersections Studied

Vehicle Type	Chenab Square	Stadium Square	Railway Square
2-Wheelers	1.08	1.12	0.96
3-Wheelers	2.05	2.17	1.44
Cars	1.98	1.88	1.99
LCV/Minibus	3.34	3.65	3.21
Buses/Trucks	6.25	6.25	6.56

Upon conducting a thorough analysis, it is evident that the saturation headway for two-wheelers at Chenab Square is around 1.08 seconds, at Railway Square it is 0.96 seconds, and at Stadium Square it is 1.12 seconds. Comparable levels of saturation headways are observed for three-wheelers in Chenab Square (2.05 seconds), Railway Square (1.44 seconds), and Stadium Square (2.17 seconds). The headways for cars at Chenab Square, Railway Square, and Stadium Square are 1.98 seconds, 1.99 seconds, and 1.88 seconds, respectively.

The saturation headway values for Light Commercial Vehicles (LCVs) and Minibuses are noteworthy due to their relatively larger values, suggesting the presence of greater time intervals between these vehicles. In this category, Chenab Square demonstrates a headway of 3.34 seconds, Railway Square exhibits a measurement of 3.21 seconds, and Stadium Square records a value of 3.65 seconds. Buses and trucks exhibit somewhat longer headway periods compared to other vehicles, as evidenced by the recorded values of 6.25 seconds, 6.56 seconds, and 6.41 seconds at Chenab Square, Railway Square, and Stadium Square, respectively.

5.2 Passenger Car Equivalent

Table 5-2 Passenger Car Equivalent of Vehicle type at Intersections Studied

Vehicle Type	Chenab Square	Stadium Square	Railway Square	IRC
2-Wheelers	0.55	0.60	0.48	0.5
3-Wheelers	1.04	1.15	0.72	1
Cars	1.00	1.00	1.00	1
LCV/Minibus	1.69	1.94	1.61	1.5
Buses/Trucks	3.16	3.41	3.30	4.50

The above table depicts the calculation of passenger car equivalents (PCEs) at three different intersections: Chenab Square, Stadium Square, and Railway Square. These calculations were performed using the headway approach. By comparing the impacts of different vehicle types with those of a standard passenger car, these values provide a quantitative understanding of how traffic flow and congestion are influenced by varying vehicle characteristics. Headway method was used to determine the passenger car equivalent in our study (Sharma, 2021).

$$PCEi = \frac{hi}{hc}$$

PCEi = PCE of vehicle category 'i'

hi = average time headway between two vehicles of type 'i' (s)

hc = average time headway between two passenger cars (s)

After careful analysis, it is evident that a two-wheeler corresponds to around 0.55 passenger car equivalents (PCE) at Chenab Square, 0.60 PCE at Stadium Square, and 0.48 PCE at Railway Square. Comparable analyses indicate that the number of three-wheelers in Chenab Square is equivalent to 1.04 passenger car equivalents (PCE), while in Stadium Square it amounts to 1.15 PCE, and in Railway Square it corresponds to 0.72 PCE. Passenger automobiles serve as the reference point, with a PCE value of 1.00 assigned to them across all intersections. This implies that a passenger car has an impact on traffic flow that is commensurate with its own presence.

Vehicles of bigger dimensions, such as Light Commercial Vehicles (LCVs) and minibuses, exhibit higher Passenger Car Equivalents (PCEs), which in turn suggest a more pronounced influence on the occurrence of traffic congestion. Light commercial vehicles (LCVs) and minibuses have a comparable value of 1.69 passenger car equivalents (PCE) at Chenab Square, 1.94 PCE at Stadium Square, and 1.61 PCE at Railway Square. Buses and trucks possess considerably higher Passenger Car Equivalent (PCE) scores due to their larger dimensions and propensity to impede traffic flow. Chenab Square, with a value of 3.16, Stadium Square, with a PCE of 3.41, and Railway Square, with a PCE of 3.30, each represent distinct locations with their respective population concentration equivalents.

The results derived from the calculations of Passenger Car Equivalent (PCE) and the criteria set out by the Indian Road Congress demonstrate a strong correlation, indicating their reliability in effectively representing the local socioeconomic circumstances and traffic dynamics. The synchronization of these indicators underscores the reliability of their ability to accurately depict traffic patterns and the wider sociocultural environment, hence augmenting their efficacy in informing infrastructure and transportation planning that is tailored to the specific requirements of the local populace.

5.3 Vehicle Distribution

A comprehensive understanding of the diverse traffic patterns in Faisalabad can be obtained by analyzing the distribution of various types of vehicles in Chenab Square, Stadium Square, and Railway Square. At these crossroads, there is a notable prevalence of two-wheelers, which constitute a significant majority of the vehicles seen. Specifically, at Chenab Square, two-wheelers account for 62.1% of the total vehicles, at Stadium Square, they make up 61.9%, and at Railway Square, they comprise 55.6%. At the various intersections, three-wheeled vehicles remain the prevailing mode of transportation, exhibiting diverse proportions: 23.3% at Chenab Square, 11.3% at Stadium Square, and 17.4% at Railway Square. In a similar vein, it is noteworthy that autos and minivans make up a significant proportion of the total, with 9.0%, 21.8%, and 23.5% at Chenab Square, Stadium Square, and Railway Square, respectively.

These intersections provide evidence of the presence of commercial vehicles, but to a lesser extent. LCVs and minibuses constitute 4.4%, 3.0%, and 3.0% of the overall traffic at Chenab Square, Stadium Square, and Railway Square, respectively. Buses and trucks exhibit a relatively modest presence in the urban traffic composition, with proportions ranging from 0.5% to 1.0%.

Table 5-3 Vehicle Distribution at Selected Intersections

Vehicle Type	Chenab Square	Stadium Square	Railway Square
2-Wheelers	62.1%	61.9%	55.6%
3-Wheelers	23.3%	11.3%	17.4%
Cars/Mini Van	9.0%	21.8%	23.5%
LCV/Minibus	4.4%	3.0%	3.0%
Buses/Trucks	0.5%	1.0%	0.4%

Taken together, these intersections exhibit the dynamic and diverse traffic patterns observed in Faisalabad. The prevalence of two-wheeled vehicles demonstrates the widespread adoption of this method of transportation, potentially attributable to its enhanced maneuverability inside urban environments. The diverse distribution of alternative vehicle types is indicative of the evolving urban infrastructure and transport needs within the metropolis. The data presented in this study holds potential value for urban planners and government organizations seeking to enhance road safety measures, optimize traffic management strategies, and improve overall traffic flow within the bustling streets of Faisalabad.

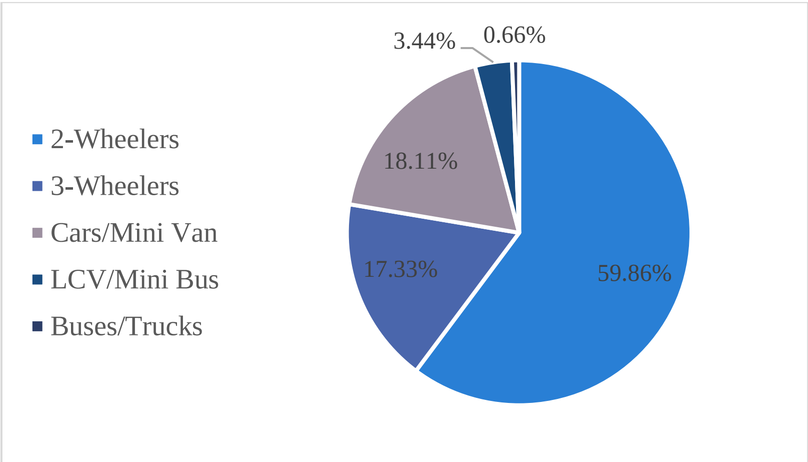

Figure 5-1 Overall vehicle Distribution of Intersections

5.4 Saturation Flow Rate

After successfully ascertaining the individual headway and calculated the passenger car equivalent, finding the average saturation headway involved the conversion of the traffic volume within a signal cycle into total passenger car units (PCU), considering the observed lanes while only using green time. The determination of the saturation flow rate, a fundamental metric in the field of traffic engineering, involves the division of 3600 by the average headway. The incorporation of this comprehensive methodology enhances the understanding of traffic dynamics and enables the fine-tuning of signal timings, leading to enhanced traffic flow and reduced congestion.

The comprehensive analysis of the saturation flow rate (SFR) data obtained from Chenab Square, Stadium Square, and Railway Square offers valuable insights into the traffic dynamics inside the city of Faisalabad. The urban transportation infrastructure of the city is dependent on these crossroads, which serve as crucial intersections. The observed flow at Chenab Square exhibits a range of computed SFR values, spanning from 1129 cars per hour, denoting the lowest recorded flow, to 2284 vehicles per hour, representing the max capacity. Comparable to Stadium Square, the observed SFR at this site exhibits a range of 1368 to 2074 cars per hour. Railway Square showcases a diverse range of SFR (Service Flow Rate) values, spanning from 1291 to 2031 vehicles per hour.

The observed disparities in the values of SFR (Saturation Flow Rate) at these specific intersections serve to underscore the diverse range of traffic patterns present within the city of Faisalabad. The traffic patterns seen in Chenab Square exhibit fluctuations that correspond to shifts in the city's demand. In Stadium Square, there are observable patterns wherein values fluctuate throughout the course of the day to mirror the varying levels of traffic. Railway Square, a prominent transport hub, has a diverse range of SFR values that replicate the intricate dynamics of automobile movement.

The presented SFR values serve as a comprehensive measure of the overall complexity of traffic in Faisalabad. The intersection's capacity to effectively handle diverse traffic volumes, which are frequently impacted by variables such as time of day, commercial operations, and special occasions, is underscored by the presence of both lower and higher SFR (Saturation Flow Rate) values. The data presented below possesses potential utility for traffic management authorities and urban planners seeking to enhance traffic efficiency, alleviate congestion, and optimize the utilization of existing road infrastructure. Faisalabad may endeavor to establish a robust traffic management system that aligns with the evolving transportation requirements of the city and promotes the creation of safer and more efficient road networks for both residents and tourists.

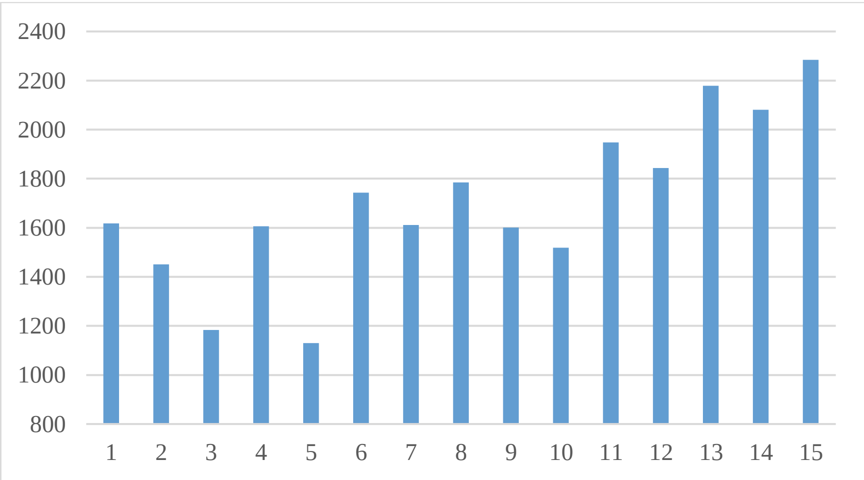

Figure 5-2 Saturation Flow Rate of different Cycles at Chenab Square

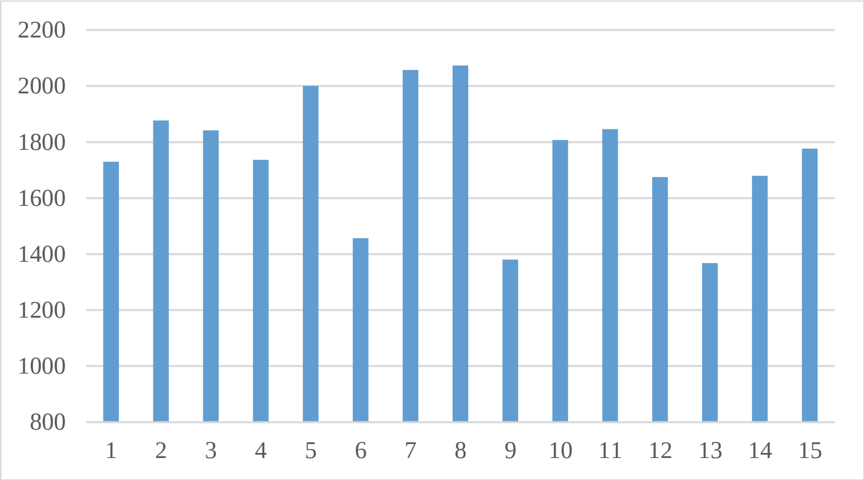

Figure 5-3 Saturation Flow Rate of different Cycles at Stadium Square

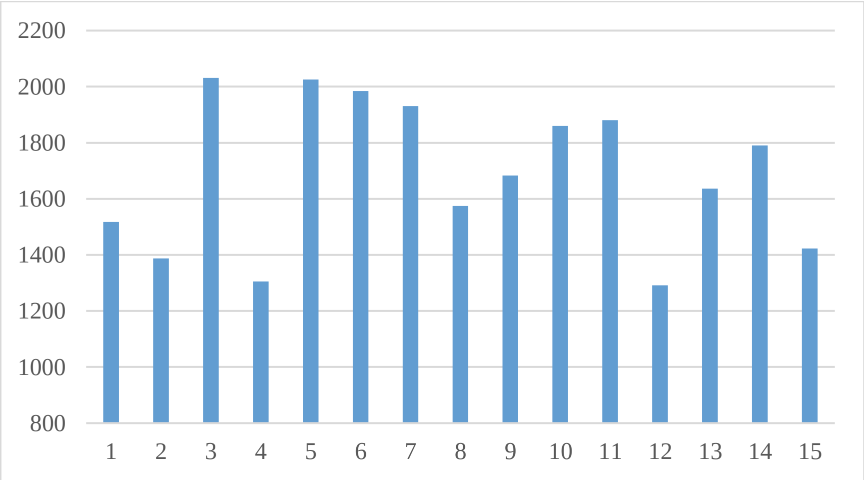

Figure 5-4 Saturation Flow Rate of different Cycles at Railway Square

By suggesting a median SFR of 1737 as the saturation flow rate for Faisalabad, prioritizing a metric that accurately reflects the average traffic flow rate experienced by individuals using the road network. This option is particularly appropriate within the framework of traffic analysis due to the inherent fluctuation in the use of roadways. The utilization of the median is justified due to its diminished vulnerability to outliers, such as occasional occurrences of high traffic rates, which have the potential to substantially influence the average SFR. Furthermore, the ability of the median to capture the central trend of the data distribution ensures that the chosen SFR serves as a reliable representation of the traffic conditions encountered by most drivers on their regular journeys.

The selected SFR value of 1737 is in accordance with a reasonable range and is consistent with findings from other relevant studies in the field. The alignment observed in our analysis offers more substantiation for the credibility of the value and enhances its pertinence within our research context. Furthermore, the integration of external research enhances the depth of analysis and facilitates well-informed decision-making within the domains of traffic planning and management.

The implementation of a saturation flow rate of 1737 vehicles per hour per lane (vphpl) can lead to improved planning and management of crossroads in Faisalabad. This approach allows for a more accurate depiction of the traffic circumstances, hence enhancing the overall effectiveness of intersection operations.

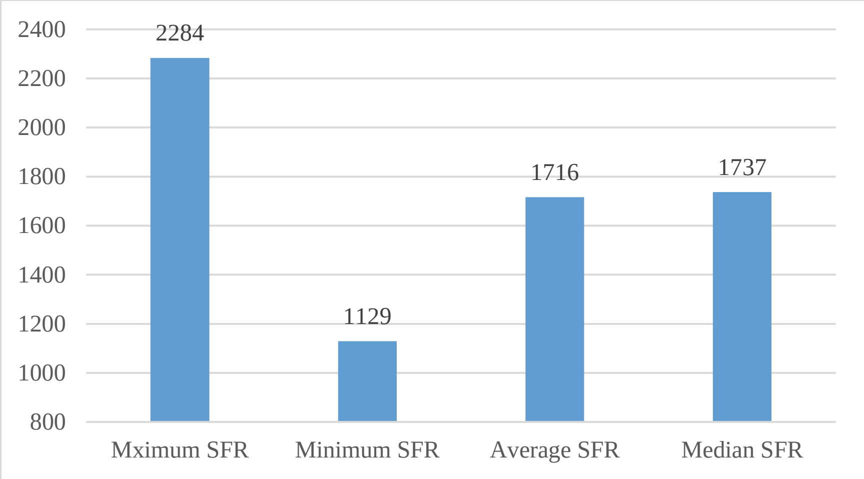

Figure 5-5 Summary of Saturation Flow Rate at all intersections

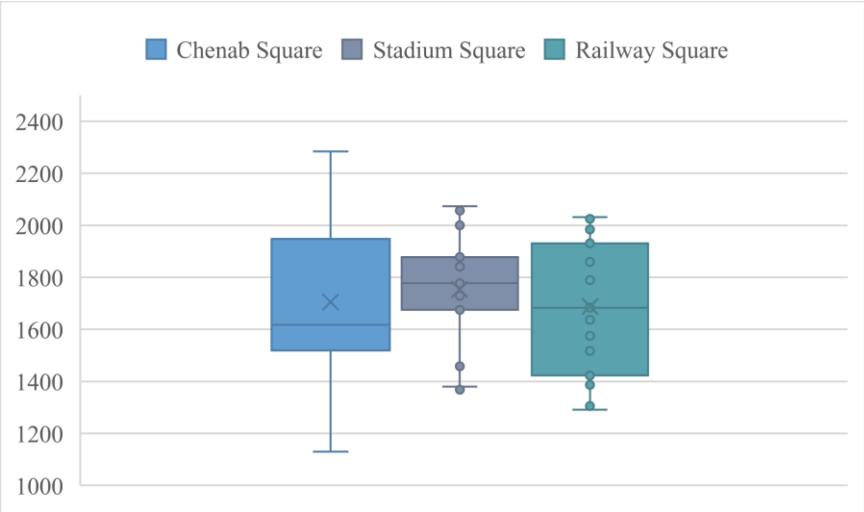

Figure 5-6 Distribution of SFR separately at selected intersections.

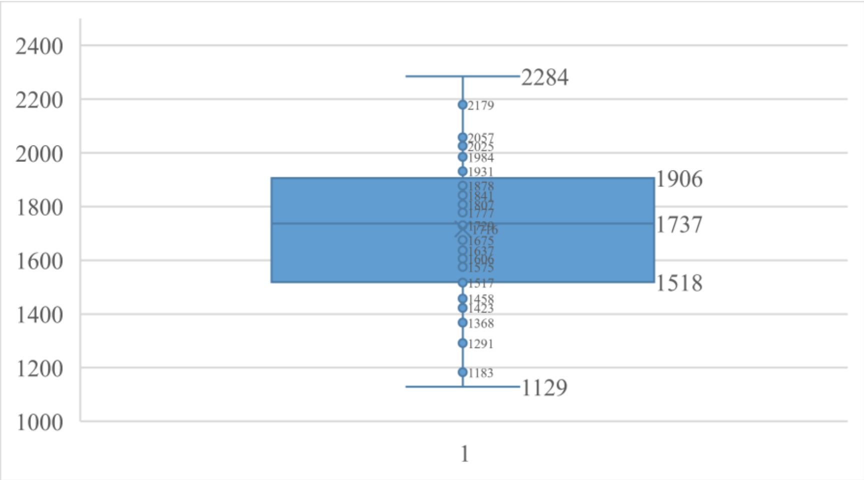

Figure 5-7 Distribution of SFR compiled at selected intersections.

5.5 Comparison With Existing Studies

Table 5-4 Saturation Flow Rate of various studies across the globe

Source	City/Country	SFR (vphpl)
Mohseni and Mirza Boroujerdian (2018)	Tehran, Iran	1905
DÃndar and Ã–ÄŸÃt (2018)	Istanbul, Turkey	1894
Rahman, Ahmed, and Hassan (2015)	Dhaka, Bangladesh / Yokohama, Japan	2006-2091 / 1636-2093
Mukwaya and Mwesige (2011)	Kampala, Uganda	1470-1774
Shawky, Al-Ghafli, and Al-Harthi (2017)	Malaysia	1945
Hussayin and Shoukry (1986)	Cairo, Egypt	1617
Coeymas and Meely (1988)	Santiago, Chile	1603
De Andrade (1988)	Brazil	1660
Bruwer, Bester, and Viljoen (2019)	South Africa	1711-2370
Chand, Gupta, and Velmurugan (2017)	India	1869-2083

The investigations, which were conducted in several urban areas across the globe, offer valuable insights pertaining to saturation flow rates and intersection capacities. They emphasized the significance of considering specific aspects such as local conditions, traffic flow patterns, and geometric attributes to accurately evaluate the performance of intersections. The results of this study (1737 vphpl) provide valuable insights for the field of transportation engineering, namely in the areas of traffic control methods and infrastructure design.

5.6 Effectiveness of New Saturation Flow Rate

The investigation on saturation flow rate has demonstrated its efficacy in ascertaining the rate at which vehicular traffic flows. The study's results have contributed to a more comprehensive comprehension of traffic dynamics, hence offering potential enhancements to traffic management systems in comparable socio-economic urban areas. The study has successfully discovered several parameters that have an impact on the saturation flow rate. These elements include the number of lanes, the kind of intersection, and the mix of traffic. By considering these elements, traffic engineers can optimize the timings of traffic signals, so enhancing the efficiency of traffic flow. Furthermore, the research has also brought attention to the constraints associated with conventional approaches for determining the saturation flow rate in a non-lane based heterogeneous traffic environment. Hence, this methodology can be advocated as a more dependable and precise approach for ascertaining the saturation flow rate. In its whole, the study offers significant insights that may be utilized by traffic engineers and policymakers to strengthen traffic management systems and improve the overall mobility and safety of the transportation system in the subcontinent.

CHAPTER 6: CONCLUSION AND RECECOMMENDATIONS

6.1 General

The newly derived saturation flow rate, as determined in this research, holds potential for application in the assessment of signalized intersection capacity and the optimization of traffic signal timings. Furthermore, it can serve as a standard against which the traffic patterns at various crossings within a certain region or across different urban areas can be compared. Hence, the newly derived saturation flow rate determined in this research can be regarded as a dependable approximation of the vehicular flow at signalized crossings in Faisalabad.

6.2 Conclusion

This study presents a methodical way for determining the Saturation Flow Rate within the framework of diverse traffic situations. By utilizing videography as a means of observation, this study presents a contemporary and non-invasive approach to assessing traffic flow at signalized crossings, hence offering a valuable tool for measuring this essential traffic metric. The Saturation Flow Rate, which is determined at a rate of 1,737 vehicles per hour per lane (vphpl) at intersections that encounter a combination of traffic conditions, provides insight into their operational efficiency.

Moreover, the congruence between our predicted Saturation Flow Rate and the results obtained in prior research conducted in many nations highlights the dependability and significance of our findings. This agreement highlights the strength and versatility of our methodology, demonstrating its potential for use in diverse urban environments. The analysis presented in this paper demonstrates the usefulness of an adaptive method in addressing complex traffic situations faced by cities worldwide. This project aims to provide urban planners and traffic engineers with practical insights to improve signal timings, optimise intersection capacities, and increase traffic flow dynamics by bridging the gap between theoretical models and real-world observations.

6.3 Recommendations

First and foremost, it is imperative to align signal timings with the traffic demand during peak periods. The minimization of congestion and the improvement of traffic flow can be achieved through the synchronization of signal timings, which is based on the observation of traffic patterns.

Additionally, it is advisable to enhance the capacity of the intersections by implementing laws such as the inclusion of dedicated turning lanes or the expansion of pre-existing lanes. This measure will enable the accommodation of the significant quantity of motorcycles and tricycles, which significantly impact the composition of traffic in Faisalabad.

Furthermore, the implementation of traffic management methods can significantly contribute to the effective management of traffic flow and the assurance of safety. This pertains to the construction of pedestrian overpasses, median strips, and traffic islands. Implementing these measures will enhance the organization and optimize the efficiency of traffic flow at the intersections.

Further investigation into the saturation flow rate is warranted, not just in Faisalabad but also in other urban areas throughout the subcontinent. The outcomes of this study can serve as a valuable foundation for future research in this sector.

In brief, the proposed recommendations encompass enhancing intersection capacity, optimizing signal timings, implementing traffic management measures, and conducting further study on saturation flow rate in Faisalabad and other cities within the subcontinent.

6.4 Further Research

Based on the findings, there exist other domains that warrant additional investigation. One potential avenue of investigation involves examining the effects of diverse traffic situations, such as fluctuating traffic volumes. A further prospective field of inquiry involves examining the impact of various intersection designs or traffic control systems on the saturation flow rate. Moreover, it is recommended to undertake additional research to explore the correlation between the saturation flow rate and many other indicators of traffic performance, such as delay or queue length. Considering the lack of lane discipline and the presence of heterogeneous traffic with a significant volume of two-wheelers.

References

[1] Abuhamda, K. H. (2015). Estimating Base Saturation Flow Rate for Selected Signalized Intersections in Doha, Qatar. *Journal of Traffic and Logistics Engineering, 3*(2), 168-171. doi:10.12720/jtle.3.2.168-171

[2] Afzal Ahmed, F. O. (2020). Examining queue-jumping phenomenon in heterogeneous traffic stream at signalized intersection using UAV-based data. *Personal and Ubiquitous Computing, 25*(1), 93-108. doi:10.1007/s00779-020-01434-y

[3] Anusha, C. S. (2013). Effects of Two-Wheelers on Saturation Flow at Signalized Intersections in Developing Countries. *Journal of Transportation Engineering, 139*(5), 448-457. doi:10.1061/(ASCE)TE.1943-5436.0000519

[4] Arasan, V. T. (2006). Estimation Of Saturation Flow Of Heterogeneous Traffic Using Computer Simulation. (A. O. W. Borutzky, Ed.) *ECMS 2006 Proceedings*. doi:10.7148/2006-0393

[5] Bara' W. Al-Mistarehi, A. H. (2020). Investigation of saturation flow rate using video camera at signalized intersections in Jordan. *Open Engineering, 11*(1), 216-226. doi:10.1515/eng-2021-0021

[6] Eri Aoyama, K. Y. (2020). Estimating saturation flow rates at signalized intersections in Japan. *Asian Transport Studies, 6*. doi:10.1016/j.eastsj.2020.100015

[7] Ghanim, M. S. (2022). Characterization of heavy vehicle headways in oversaturated interrupted conditions: Towards development of passenger car equivalency factors. *International Journal of Transportation Science and Technology, 11*(3), 589-602. doi:10.1016/j.ijtst.2021.07.002

[8] *Google Images*. (2023). Retrieved from https://images.google.com/

[9] Guo, Y. (2012). Effect of Bicycles on the Saturation Flow Rate of Turning Vehicles at Signalized Intersections. *Journal of Transportation Engineering, 138*(1), 21-30. doi:10.1061/(ASCE)TE.1943-5436.0000317

[10] Iqbal M J, Q. A. (2011). Estimation of saturation flow at thirteen (13) signalized junctions of Shahra-e-Faisal, Karachi. *International Road Safety Conference, 2007, Perth, Western Australia.*

[11] Kara M. Kockelman, R. A. (2000). Effect of Light-Duty Trucks on the Capacity of Signalized Intersections. *Journal of Transportation Engineering, 126*, 506-512. Retrieved from https://api.semanticscholar.org/CorpusID:109209365

[12] Liu, C.-q. S.-m. (2012). Estimation of Saturation Flow Rates at Signalized Intersections. *Discrete Dynamics in Nature and Society*, 1-9. doi:10.1155/2012/720474

[13] Liu, P. (2011). Evaluating the Impacts of Unconventional outside Left-Turn Lane Design on Traffic Operations at Signalized Intersections. *Transportation Research Record: Journal of the Transportation Research Board, 2257*(1), 62-70. doi:10.3141/2257-07

[14] Long, G. (2008). Driver Behavior Model of Saturation Flow. *Transportation Research Record: Journal of the Transportation Research Board*, 65-72. doi:10.3141/2027-09

[15] Manjul Sharma, S. B. (2021). Estimation of Passenger Car Unit on urban roads: A literature review. *International Journal of Transportation Science and Technology*, *10*(3), 283-298. doi:10.1016/j.ijtst.2020.07.002.

[16] Mathew, R. K. (2021). Estimation of saturation flow for non-lane based mixed traffic streams. *Transportmetrica B: Transport Dynamics, 9*(1), 42-61. doi:10.1080/21680566.2020.1781708

[17] Mondal, S. (2020). Comparative analysis of saturation flow using various PCU estimation methods. *Transportation Research Procedia, 48,* 3153-3162. doi:10.1016/j.trpro.2020.08.168

[18] Preethi, P. (2018). Modelling saturation flow rate and right turn adjustment factor using area occupancy concept. *Case Studies on Transport Policy, 6*(1), 63-71. doi:10.1016/j.cstp.2017.11.001

[19] Preethi, P. (2019). Estimation of saturation flow under heterogeneous traffic conditions. *Proceedings of the Institution of Civil Engineers - Transport, 172*(1), 1-11. doi:10.1680/jtran.16.00088

[20] Radhakrishnan, P. (2011). Passenger car units and saturation flow models for highly heterogeneous traffic at urban signalised intersections. *Transportmetrica, 7*(2), 141-162. doi:10.1080/18128600903351001

[21] Rahman, M. &. (2005). Comparison of saturation flow rate at signalized intersections in Yokohama and Dhaka. *Proceedings of the Eastern Asia Society for Transportation Studies, 5,* 959-966. Retrieved from https://www.easts.info/on-line/proceedings_05/959.pdf

[22] Rakha, H. A. (2004). Performance Evaluation of Signalized Urban Intersections under Mixed Traffic Conditions by Gray System Theory. *Journal of Transportation Engineering, 130*(1), 113-121. doi:10.1061/(asce)0733-947x(2004)130:1(113)

[23] Shao, C.-q. (2011). Study on the Saturation Flow Rate and Its Influence Factors at Signalized Intersections in China. *Procedia - Social and Behavioral Sciences, 16,* 504-514. doi:10.1016/j.sbspro.2011.04.471

[24] Sharma, M. (2021). Estimation of Passenger Car Unit on urban roads: A literature review. *International Journal of Transportation Science and Technology, 10*(3), 283-298. doi:10.1016/j.ijtst.2020.07.002

[25] Teply, S. a. (1991). Capacity of signalized intersections: Canadian Capacity Guide for Signalized Intersections. Transportation Association of Canada. https://doi.org/10.3141/1572-04.

[26] Wang, L. (2018). Automatic Estimation Method for Intersection Saturation Flow Rate Based on Video Detector Data. *Journal of Advanced Transportation*, 1-9. doi:10.1155/2018/8353084

[27] Wang, Y. (2013). Study on Traffic Safety Evaluation Based on Traffic Conflict Technique and Gray Clustering at Signalized Intersection. *ICTIS 2013*. doi:10.1061/9780784413036.176

[28] Wang, Y. (2020). An Analysis of the Interactions between Adjustment Factors of Saturation Flow Rates at Signalized Intersections. *Sustainability, 12*(2), 665. doi:10.3390/su12020665

[29] Wang, Y. (2020). Dynamic Estimation of Saturation Flow Rate at Information-Rich Signalized Intersections. *Information, 11*(4), 178. doi:10.3390/info11040178

[30] Washburn, S. S. (2010). Impact of Trucks on Signalized Intersection Capacity. *Computer-Aided Civil and Infrastructure Engineering, 25*(6), 452-467. doi:10.1111/j.1467-8667.2010.00651.x