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Microscopic Traffic Congestion Analysis and Optimization: A Case Study

by

Muhammad Yahya

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degree of Master of Science

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Muhammad Yahya

Abstract

Highways are the backbone of modern transportation systems, crucial for urban mobility, economic growth and efficient goods and services delivery. However, the rate of urbanization and vehicular traffic in developing countries has consistently exceeded the capacity of the road network to meet the demand resulting in high and severe levels of congestion. The traffic flow in the cities of South Asian countries like Islamabad is heterogeneous comprising of motorcycles, auto-rickshaws, cars and heavy vehicles. This study aims to reduce urban traffic congestion by analyzing the behavior of Kak bridge Intersection using a microscopic simulation tool named SUMO (Simulation of Urban Mobility) with an objective to develop a calibrated and validated SUMO model that would realistically describe the local mixed traffic behavior and that would allow for comparison of evidence-based intervention measures for reduction of delay and improvement of operational performance.

The methodology consists of field data collection (traffic volume, turning movements, GPS travel-time surveys and geometric surveys), building a SUMO network model, calibration and validation using the GEH statistic, and simulation of three progressively advanced scenarios for improvement: parking management, Webster-optimized fixed-time signalization, and actuated signal control. The results showed that the present intersection was operating at a LOS E-F with an average waiting time of 72.08 seconds and 1,359 vehicles unable to enter the network per day. Also, the parking management reduced the waiting time by 51.9%, fixed-time signalization reduced it by 61.4% and actuated control resulted in the maximum reduction of waiting time by 74.0% and improved the LOS to D. The study recommends for future work to model the approach on similar signalized intersections across Pakistan to develop a national evidence base for simulation-based traffic engineering, inclusion of deep reinforcement learning (DRL) based signal control, modeling of corridor-level simulation with adjacent junctions and detailed modeling of emissions.

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List of Abbreviations

ACS	Adaptive Control Software
AI	Artificial Intelligence
AIMSUN	Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks
API	Application Programming Interface
BL	Baseline
CDA	Capital Development Authority
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
DLR	Deutsches Zentrum fr Luft- und Raumfahrt (German Aerospace Centre)
DQN	Deep Q-Network
DRL	Deep Reinforcement Learning
GEH	Geoffrey E. Havers
GHR	Gazis Herman Rothery
GPS	Global Positioning System
HBEFA	Handbook of Emission Factors for Road Transport
HCM	Highway Capacity Manual
HGV	Heavy Goods Vehicles
ICT	Islamabad Capital Territory
IDM	Intelligent Driver Model

ITS	Intelligent Transportation System
LOS	Level of Service
LWR	Lighthill Whitham Richards
MAPE	Mean Absolute Percentage Error
MC	Motorcycles
MG	Maximum Green
MGI	Maximum Gap Interval
NHA	National Highway Authority
NO _x	Nitrogen Oxides
NUTECH	National University of Technology
OD	Origin Destination
OSM	OpenStreetMap
OSMS	Open-source Micro-Simulation
PC	Passenger Cars
PCU	Passenger Car Unit
PM	Particulate Matter
PTV VIS-SIM	Planung Transport Verkehr Traffic in Cities - Simulation Model
RDA	Rawalpindi Development Authority
RMSPE	Root Mean Square Percentage Error
SAC	Soft Actor Critic
SCATS	Sydney Coordinated Adaptive Traffic System
SCOOT	Split, Cycle and Offset Optimisation Technique
SDG	Sustainability Development Goals
SSAM	Surrogate Safety Assessment Model
SUMO	Simulation of Urban Mobility
TMC	Turning Movement Counts
TRANSYT	Traffic Network Study Tool

UAV	Unmanned Aerial Vehicle
XML	Extensible Markup Language

Chapter 1

Introduction

1.1 Background

The foundation of urban economic growth is transport infrastructure, which makes it easier for people and goods to move around, which is crucial for a modern economy [1]. However, the rate of population growth and increasing car ownership in developing countries has kept up with the development of infrastructure, leading to severe traffic congestion that has an impact on quality of life, productivity, and the environment [2]. When demand rises above capacity, traffic congestion develops, leading to slower speeds, longer travel times, and a significant amount of vehicle queuing [3–5].

However, intersection congestion and delays are still an issue. This occurs even in the most developed nations with densely populated urban centers and high traffic. Congestion is estimated to cost the US economy \$87 billion. The cost per driver was estimated to be 97 hours annually in 2018 [6–8]. The same issue affects the capital cities of Europe. London, for instance, is frequently listed as one of the most congested cities. Every year, drivers in this city lose about 148 hours due to traffic [9, 10]. Thus, it is clear that traffic congestion at intersections is a global issue that affects all economic development levels [11–13]. Regular travels and commercial operations are affected by ongoing traffic, and construction closures add even more diversity that demands careful simulation analysis. Recently, it has

been determined that microscopic simulation is a valuable technique for examining complicated connections [13–15]. SUMO (Simulation of Urban Mobility) is a flexible open source microscopic and dynamic traffic simulation software which was initially developed by the German Aerospace Center (DLR). The initial version of SUMO was designed to provide a framework for the modeling of urban transport systems and is continuously enhanced by a worldwide community of researchers and developers. The software uses advanced, microscopic vehicle behavior models such as the Krauss Car-Following Model and the Intelligent Driver Model (IDM) to simulate realistic driver-vehicle interactions and reproduce traffic flow characteristics [12, 16–18].

A global issue that has impacted practically every nation, particularly the developing ones, is traffic congestion. The issue is made more severe in these nations by insufficient infrastructure to keep up with the rate of development [2, 5, 19]. There are two types of traffic jams: the unpredictable ones, which are typically brought on by accidents, road construction, and other significant activities, and the predictable and recurrent ones, which are typical during rush hour [3, 5, 10, 20]. The amount of fuel used while stuck in traffic, the amount of time wasted, and the amount of pollution produced make this issue costly [21, 22]. The facts are concerning, and the issue is equally severe in developed nations. For instance, it was estimated that traffic congestion cost the US economy \$87 billion in 2018. Every year, a driver in this nation loses about 97 hours due to traffic. Large cities in Europe are not unaffected by this issue [4, 6, 7]. Every year, a driver in London, one of the world’s most congested cities, loses about 148 hours due to traffic [9]. Regardless of how advanced a nation’s infrastructure is, this issue is universal and not specific to any one nation, developed or developing [11, 12, 23].

To reduce traffic at intersections, a number of strategies have been developed. Congestion at signalized intersections can be reduced by 20 - 30% by optimizing the signal timings by changing the length and distribution of the signal cycles [24]. When compared to fixed-time signals, automated signals help reduce waiting periods by up to 70% on major approaches and by 39% at busy intersections [16]. Potential problems at intersections where the turning movements are not balanced

can be addressed by geometric improvements like adding lanes, extending turning bays, and widening approach lanes [25, 26]. The roadside congestion points are addressed by traffic management techniques like limiting access, limiting on-street parking, and improving pedestrian facilities [27]. The delay caused by heavy vehicles could be reduced by 50% through signal optimization utilizing connected vehicle technologies and the team's concept [25, 28]. Roundabouts, flyovers, and underpasses are examples of infrastructure upgrades at extremely congested intersections [29]. Microscopic simulation has become an essential tool for assessing the effectiveness of solutions created at intersections before they are put into practice [14, 23, 24, 29].

The global tool in microscopic traffic simulation is SUMO (Simulation of Urban Mobility), which was created by the German Aerospace Center [13, 17, 30]. It makes use of the Wiedemann car-following model, a psycho-physical model that simulates how drivers respond to following distance and acceleration/deceleration limitations [15, 18, 31]. It provides a full range of tools for interchange analysis, such as the ability to simulate mixed traffic with various vehicle types, simulate intersections with various forms of control, and analyses queue length, delay, travel time, and level of service [32]. It is also possible to calculate emissions and fuel consumption, and to show the results to stakeholders, 2D and 3D visualizations can be made. It is crucial to make sure the model is calibrated effectively because the preset parameters are based on European driving habits, whereas the traffic conditions in developing nations are varied and different. Target speed distributions, lane-change maneuvers, gap acceptance, and car-following thresholds (CC0 to CC9, according to the Wiedemann 99 model) are among the crucial calibration parameters [16]. The model can be validated using statistics like the Geoffrey E. Havers (GEH) distance, where values less than 5.0 are good, and the Mean Absolute Percentage Error (MAPE), where values less than 10 to 15 percent are acceptable [11, 12, 17, 23]. Since earlier research has demonstrated the importance of microscopic simulation models for intersection analysis, no study has been done on complicated interchange designs in Pakistani cities that incorporate local road access and congestion points in addition to arterial mainline traffic. Additionally, the selected interchange has unique characteristics, necessitating special

attention. All of this leads to set of operational challenges that conventional intersection models are unable to handle. Hence, this study aims to close the gap by creating and verifying a calibrated microscopic simulation model for one such crucial interchange.

This study examines traffic congestion at Interchange using SUMO and offers evidence-based optimization techniques. This study will try to provides understanding of the root causes behind traffic jams and offer workable solutions by combining field data with thorough simulation modeling that is adapted to developed driving practices to enhance sustainability.

1.2 Research Motivation and Problem Statement

This research is motivated by the need for effective and evidence-based solutions to growing urban traffic congestion in developing countries such as Pakistan. Increasing traffic demand and limited road capacity make intersections critical points of delay, queuing, and inefficient traffic flow, highlighting the need for scientifically informed and cost-effective congestion mitigation. Among intersection configurations, T-junctions are particularly important as connections between major and minor roads, while their role becomes more critical in grade-separated networks where transition ramps connect with surface roads. Such ramp - road interfaces can involve complex traffic interactions and localized congestion, directly affecting network efficiency. Accordingly, this research is motivated by the need to better understand and improve traffic operations at these critical junctions, with the broader aim of achieving congestion-free T-intersections in developing countries such as Pakistan (Figure 1.1).

The problem statement is:

“The development of arterial mainline traffic, local commuter movement, and numerous roadside challenges causes severe regular congestion at Kaak Bridge Interchange, resulting in excessive delays, fuel waste, and commuter discomfort; however, the lack of advanced traffic analysis and evidence-based optimization strategies leaves the transportation sector without scientific basis for effective measures,

necessitating this simulation-based investigation.”



FIGURE 1.1: Congestion Free Intersection showing smooth traffic flow

1.2.1 Research Questions

- i. How is the current unsignalized, police-controlled operation of the Kaak Bridge T-junction performing in terms of queue lengths, delay, travel time and Level of Service?
- ii. What approach could be used to realistically represent the heterogeneous traffic conditions at the Kaak Bridge T-junction (mixed vehicles and unsignalized control)?
- iii. What is the most feasible optimization method that could be used at the Kaak Bridge T-junction, and what is the proposed order of action for implementation?

1.3 Overall Aim and Specific Goal of this MS Research

The overall aim is to expand global efforts to reduce urban traffic congestion through a comprehensive microscopic examination of the issue and the development of evidence-based optimization strategies. The specific goal of research is

to develop a simulation model that accurately shows the mixed traffic conditions by using driver behavior parameters that have been checked with GEH statistics and MAPE and to compare different optimization methods, such as improving signalization, making geometrical changes, and using access management strategies, to find the best way to reduce traffic congestion, minimize delays, and lower emissions at this important traffic intersection. This study will demonstrate how simulation-based approaches may lead to sustainable transportation solutions for rapidly urbanizing areas.

1.4 Scope of Work and Study Limitations

This study emphasizes on the micro-level traffic challenges and modifications at the Kaak Bridge interchange of the Expressway on Kahuta Road in Islamabad. This area was selected for this study because it is known for having a lot of traffic and congestion during rush hour.

This study is limited to simulation analysis by using SUMO software with parameters acquired from the field. It is limited to advance to the phase of executing it on site or the phase of evaluating it. The results are also only valid for the selected interchange and may not be easy to apply to other interchanges. Reconstruction of the interchange is beyond the scope of this specific study.

1.4.1 Rationale behind Variable Selection

The analysis of microscopic traffic optimization is critical since most conventional analyses of road intersections have concentrated on basic intersections, ignoring the particulars of interchanges where multiple streams of traffic converge, with roadside congestion points also involved. In this case, the advanced simulation optimization technique is the only option for the assessment of optimization strategies prior to costly implementation [6, 8, 20]. Also, the use of the simulation technique is critical for the scientific assessment of road congestion, with the option of evaluating different scenarios without the need for costly disruptions of the natural

flow of traffic. In this case, the conventional techniques cannot provide the same option. Hence, the use of the SUMO simulation technique is the globally accepted option for the optimization of road traffic, but it has not been applied in developing countries such as Pakistan, where the majority of the population use passenger cars at the rate of 55%, motorcycles at the rate of 42%, with the remaining light vehicles [9, 33]. The selection of the Kaak Bridge interchange was critical since it is one of the critical roads with no prior analysis of the road interchange ever conducted despite the presence of critical congestion problems. The scenario set follows the same logic, progressing from the least expensive operational measure (parking management) to moderately expensive signal infrastructure (fixed-time signalisation) and finally to technology-based adaptive control, consistent with the incremental deployment pathway documented for Pakistani urban intersections [8, 33]. This progression ensures that each scenario's benefit is measured against the one preceding it, so that costlier interventions are adopted only once the value of lower-cost measures has been established.

1.5 Research Impact on Industry

1.5.1 Industrial and Academic Collaborator Roles

This research is organized as a joint academic-industry project to ensure the methodological compatibility and realism. The academic supervisor offers support in the field of simulation modeling, calibration and research methodology, which ensures that the research study aligns with the engineering standards. Potential industrial and institutional partners include the National Highway Authority (NHA), with their experience in operation of the motorway contributing to context-specific approaches for traffic management in practice; Rawalpindi Development Authority (RDA), for their local knowledge of urban transport planning and integration of land-use in the twin-city context; Islamabad traffic police for the empirical data pertaining to traffic volume, incidents and enforcement activities available at the intersection level; and the National university of technology (NUTECH) who have previous research experience related to intersection-level

studies in Islamabad, providing a methodological reference point. The result is an academic and field level robust multi-stakeholder research output.

1.5.2 Research Novelty - Uniqueness

This simulated study of the Kaak Bridge Intersection addresses a topic that has received limited attention in the literature and offers three practical contributions to existing regional traffic-infrastructure research. First, it adopts locally derived Pakistani driver-behavior data for each of the five vehicle categories, rather than relying on a single, network-wide parameter set as in comparable regional SUMO studies, thus better reflecting the real behavioral difference between irregular, gap-filling motorcycles and cars and the more consistent, larger-headway movement of buses and trucks, and directly improving the reliability of the resulting delay, queue, and emissions estimates. Second, this is the simulated study of a junction that is geometrically distinct from the at-grade T-junctions typically examined in the literature: a transition ramp connects directly to one arm of the junction, adding a ramp-merge conflict to the standard unsignalized priority conflict. Third, the study compares a staged sequence of interventions of increasing cost, providing an implementing authority with a validated basis for justifying investment, and explicitly incorporates vehicular emissions into the optimization alongside delay and capacity.

1.5.3 Research Significance and Benefits

The overall objective of this research is to develop evidence-based and data-driven recommendations which will help transport authorities to efficiently allocate infrastructure and operational resources. Individual road users will benefit from lower travel times, lower fuel use and less stress due to improved traffic flows and reduced congestion. On the commercial impact, improved access and lower logistics expenses will be expected to be advantageous for local companies that have a dependence on smooth goods and staff transportation. Environmentally, the decrease in vehicle idling duty at the interchange will be measurable reductions in emissions and will improve local air quality. In addition to these applied benefits,

the study is a valuable addition to the existing academic research on microscopic traffic simulation, especially in the context of developing countries, in which infrastructure, driver behavior and data availability may vary significantly from those of most simulation frameworks.

1.5.4 Practical Implementation

Recommendations from this study are developed with the emphasis of practicality. This involves reviewing the possibility of coordinating proposed work with the existing road infrastructure, examining the financial costs of the proposed work and ensuring that it is cost-effective, as well as considering the physical and logistic limitations of the site of the interchange. This practical approach is designed to increase the chance that the findings from the study are put into practice and do not remain theory.

1.5.5 National and Global Impact with SDGs Relevance

The research is relevant to several United Nations Sustainable Development Goals (SDGs):

SDG 3: By lowering the risk of accidents and promoting cleaner air, it maintains good health and wellbeing.

SDG 11: By improving mobility, it seeks to create sustainable cities and communities.

SDG 13: By lowering vehicle emissions, it encourages climate action.

The research can help inform the public health outcomes of commuters and people living near the commuter rail line, by identifying interventions that can decrease the risk of accidents and improve air quality. The research helps to create more sustainable and accessible urban mobility systems by optimizing mobility and traffic flows. The study's efforts to reduce emissions from vehicles, by addressing idling and vehicle flow, aid in the broader climate action agenda at a local level.

1.5.6 Research Challenges

A number of methodological and logistical challenges are expected throughout the process of this research. When conducting data collection at a high-volume interchange, the selection of data collection days must be carefully planned to avoid data collection on a typical day and multiple observers must be coordinated to ensure accurate and consistent data collection. Another difficulty is the calibration process required for the model, especially since real-world traffic conditions are subject to variation, making it difficult to obtain a simulation model that closely represents traffic conditions in the real world. The scope and flexibility of the analysis is also limited by restricted availability of specialized simulation software. Together, these challenges require a well-thought-out approach for data collection and data calibration to ensure the validity and strength of the conclusions drawn from the study.

1.5.7 Ethical and Management Considerations including Risk Management

With a primary focus on field personnel safety and data integrity, empirical traffic parameters were strictly harvested from designated safe, low-traffic vantage zones along the intersection buffer. The structural confidentiality of the observed commuters has been meticulously maintained by ensuring no personal identifiers, vehicular license numbers, or individual driver tracking data were permanently logged, keeping the processed database entirely anonymized, accurate, and scientifically unaltered. To address operational contingencies, a robust risk management protocol was deployed to account for unexpected fieldwork uncertainties. Comprehensive mitigation plans were established to combat field equipment failures, sudden battery depletions, and unfavorable meteorological conditions such as monsoonal rain or extreme dust storms by utilizing dual back-up counting hardware and scheduling flexible, multi-day observation windows to ensure uninterrupted, high-fidelity data collection.

1.5.8 Research Deliverables

The primary technical outputs generated from this research program consist of a fully calibrated and validated microscopic SUMO simulation model along with an extensive, highly granular traffic volume and geometric database tailored for South Asian traffic mix conditions. Based on these core models, the research delivers an advanced performance assessment matrix derived from rigorous comparative scenario evaluations and robust, data-backed engineering recommendations. The secondary scholarly outputs include a comprehensive final thesis manuscript detailing the intersection dynamics, accompanied by peer-reviewed research drafts intended for publication in impact-factor journals and presentation at international transportation conferences. Additionally, the study delivers an actionable policy brief outlining localized immediate-to-medium term traffic interventions for municipal authorities, alongside a generalized microscopic simulation methodology manual engineered to serve as a replication blueprint for future urban congestion research.

1.6 Brief Methodology

The methodology includes six different phases. In phase 01, geometric data, signal timing data, turning movements, traffic volume, vehicle types, and travel time studies are all collected [12,17,26]. The model is developed in phase 02 by creating the road network, vehicle mix, traffic input, routing decisions driving parameters, and possible conflict zones [31]. In phase 03, model authenticity is ensured through calibration and validation. The MAPE method, GEH checks where $GEH < 5$, and visual checks are used to achieve this [13,17,34]. Phase 04 includes the scenario development by developing the plan for improvement. This can be done by using the combined approach to run several simulations [16]. In phase 05, performance evaluation includes evaluating how well the scenarios perform. Queue length, delay, travel time, LOS, and emissions are used to attain this [35]. Then in phase 06, the scenarios are compared through comparative analysis. Quantitative, statistical, and multi-criteria analysis are used to carry out this [2,5,7,19].

1.7 Thesis Layout

There are six chapters in this thesis, the brief details of these chapters are as follows:

Chapter 1 provides the foundational context for the research, including the background of urban traffic congestion, research motivation, problem statement, and specific research questions. It outlines the overall goal of the research program, the scope of work and study limitations, the research impact on the industry, and the research deliverables. A brief summary of the methodology is also presented.

The literature review in Chapter 2 outlines the nature, causes, and consequences of urban traffic congestion. It reviews potential solutions for traffic management, ranging from signalized intersection analysis and roundabout performance to advanced signal control methods, such as Webster's method and Deep Reinforcement Learning (DRL). It also discusses simulation modeling as an engineering approach, with a specific focus on microscopic simulation platforms and the SUMO (Simulation of Urban Mobility) software, highlighting its application in South Asian and developing-country contexts.

The research methodology is detailed in Chapter 3, which describes the Kaak Bridge intersection study area and the comprehensive field data collection framework, including classified traffic volumes, turning movement counts, GPS floating-car surveys, and geometric surveys. It further covers the building of the SUMO network model, the vehicle-type definitions and car-following parameters, the calibration procedure using the GEH statistic, validation protocols, and the development of three progressively advanced improvement scenarios: parking management, Webster-optimized fixed-time signalization, and actuated signal control.

Chapter 4 focuses on the results and analysis of the simulation. This includes the validation of the calibrated model against field data, the assessment of the baseline scenario (S0), and the comparative evaluation of the three improvement scenarios (S1, S2, and S3). Performance metrics such as average vehicle delay, queue length,

throughput, Level of Service (LOS), and environmental impacts (CO₂ emissions and fuel consumption) are analyzed, and the findings are discussed.

The engineering recommendations for implementation are presented in Chapter 5, covering practical measures categorized into immediate (Tier 1: Parking Management), short-term (Tier 2: Webster-optimized signalization), and medium-term (Tier 3: Actuated signal control with ITS integration). This chapter provides an implementation road map and aligns the recommendations with sustainability goals and SDG relevance.

Chapter 6 presents the key conclusions drawn from the study and offers recommendations for future research, including expanding the evidence base to other unsignalized intersections, integrating DRL-based control, and performing corridor-level and emission-focused modeling. References are provided at the end of the thesis.

Chapter 2

Literature Review

2.1 Background

Highways are the most significant component of a country's physical infrastructure. They are the main roads that people, goods, and services travel on between towns, villages, and other cities. Highway networks are an important part of the construction industry because they support almost every part of modern economic operations. They allow raw materials to move to production centers, finished goods to markets, and workers to job centers. Their capacity, connectivity, and operational efficiency are directly related to the efficiency and competitiveness of the economies they support [10, 19]. Highways serve an important social purpose in addition to their economic one. They connect communities, make it easier for people to get to health-care, education, and public services, and help people from different regions and countries live together in the same area [36, 37].

Because of this basic importance, governments all over the world have invested a lot of resources into building, expanding, and maintaining highway infrastructure as part of their national development budgets. They consider investing in roads as a key part of long-term plans for economic growth [5]. In Pakistan, highways and urban road networks are not only the main way to move people and goods, but they are also a very important way to bring the country together by connecting provinces, cities, and economic zones. This is because the country's

geography and development patterns make its surface transport system very demanding [6,26]. In the past half-century, the population of cities around the world has grown quickly. This has made traffic jams a bigger problem that affects the economy, the environment, and society as a whole. In both developed and developing nations, there exists a strange situation in which the identical infrastructure of roads, intersections, and regulated pathways that promote economic activity simultaneously becomes a hindrance as escalating motorization exceeds the capacity of these infrastructures [10,19].

The roads all over the world are under significant amounts of traffic because cities are growing so quickly. The roads that used to be functional highways are now severely congested roadblocks that hurt the economy, the environment, and public safety. The main roads that connect cities and towns in a country are highways [5,13,36]. Highways are supposed to make it easy for people and things to move quickly and without stopping over long distances. However, in many developing countries, these same roads are now being used more than they were meant to be used for most of the day. The resulting traffic jam isn't just a discomfort; it's a structural failure of the transportation system that has effects on many parts of society that can be measured and get worse over time [10].

The resulting congestion is beyond just an inconvenience; it is a failure of the transport system that has measurable and combined effects on numerous sectors of society. The time wasted on travel makes workers less productive and raises the cost of logistics. Using too much fuel costs both families and the country funds as well speeds up the release of greenhouse gases. Heavy traffic on highways raises the risk of rear-end and multi-vehicle accidents, which can be bad for people's health and the economy [37]. In cities that are growing quickly, like those in Pakistan, where the number of cars is rising quickly but infrastructure investment has consistently fallen behind consumption, traffic jams on highways have become an essential aspect of city life and a known barrier to economic growth [6,38].

The problem becomes more severe by the fact that motorcycles, auto-rickshaws, buses, and heavy goods vehicles all use the same public road space in South Asian cities without following lane discipline [39]. This lowers the effective capacity of

highways well below their geometric potential and makes it hard to use standard Western traffic management solutions both technically and functionally [26, 40]. And to resolve this, we have to invest resources into physical infrastructure in addition to collect a lot of data that shows how bad traffic is in some areas, what causes it, and how well different solutions work before we spend our resources on them. The most effective way to do this is with modern traffic simulation methods [18, 41].

It is the combination of severe and under-managed congestion and the operation constraints of traditional Western planning tools that motivate the present study. Kaak Bridge Intersection on Islamabad Expressway is one such intersection: a three-arm, high-volume intersection that is completely unsignalized and uses traffic police to manage it in real time, leading to a chronic and measurable delay and loss of capacity as described above. The global and regional congestion problem described in this section is illustrated here with a case study of Kaak Bridge.

2.1.1 Urban Traffic Congestion: Nature, Causes and Consequences

Congestion is one of these concepts which almost everyone has experienced but is rather hard to pin down in precise terms. From an engineering point of view, congestion is when the demand for travel space on a certain facility at a certain time is higher than its capacity. This causes the speed to slowly go down, the headway to go up, and queues to form backwards from the area where capacity is limited [19]. The supply-demand approach defines congestion in terms of measurable variables like flow, density, and speed. The engineering perspective, on the other hand, doesn't take into account the fact that capacity depends on things like the structure of the vehicle fleet, driver behavior, the layout of the facilities, the weather, pedestrians, and non-motorized traffic [26].

This is the reason that multiple overlapping theoretical models have been proposed. Travel time-based models state that congestion happens when the actual travel time on a certain link is longer than the travel time when there are no

delays. In this case, the model is highly relevant as it reflects the actual travel time experienced by motorists during their journey [6]. Economic models describe congestion as a difference between the costs incurred by the user (the traveler) and the social costs linked to the journey. In this context, congestion generates adverse effects as the costs incurred by one user on another are not considered in the user's decision-making process, necessitating policy interventions [37]. The significance of non-recurring and recurring sources has its impact on the management strategies since recurring congestion can be addressed through infrastructure development and signal optimization, but non-recurring sources require the implementation of an incident management system and building a robust network [19]. The classification of congestion types (recurring and non-recurring) is shown in Figure 2.1.

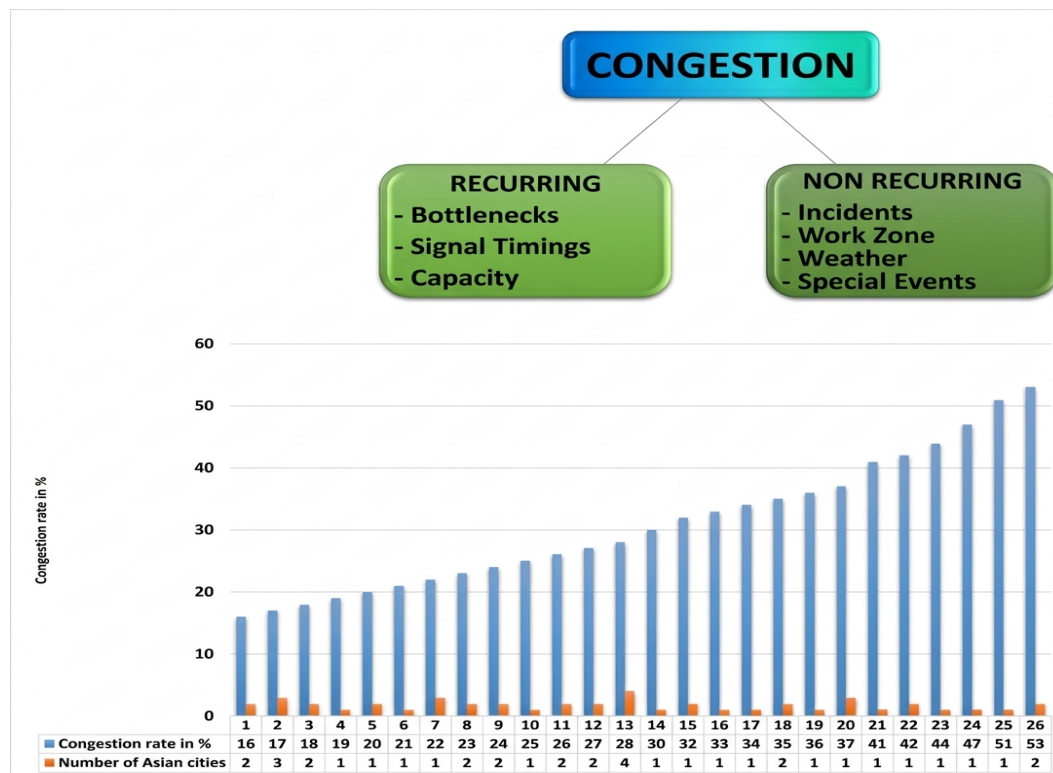


FIGURE 2.1: Classification of congestion types (recurring vs. non-recurring) and Asian city congestion rates [10]

But all of these points aren't incompatible because they show different sides of a situation that is naturally multi-dimensional. Consequently, a singular dimension measure is inadequate to encompass the concept of congestion; both point-level capacity measures and network-level flows require management [19].

2.1.1.1 Causes and Contributing Factors

A number of authors propose that there are many reasons why traffic jams happen in cities. There are two main types of causes: structural, which are due to the method land is used and the number of people living there, and operational, which are due to actual processes for managing traffic flow. Rapid urbanization is considered as the primary contributor to structural congestion, as population growth results in a corresponding rise in travel demands and, consequently, in the number of registered vehicles, which frequently exceed road capacity [10, 36, 37] conducted a comprehensive analysis of the structural causes of traffic congestion, utilizing structural equation modeling to assess structural traffic factors across 100 metropolitan areas in the USA.

The researchers discovered that wealth and employment concentration significantly contribute to increased congestion, while alternative transportation methods and a dense urban structure serve as the most effective means to mitigate these trends. Additionally, the role of population has been demonstrated to be insufficient for estimating the probability of congestion [42]. The sources of traffic congestion due to operations are even more numerous. According to [36], poor intersection design, inadequate road capacity, uncoordinated traffic signals, and lack of proper enforcement of traffic rules emerge as the top recurring factors, whereas accidents, construction work, and bad weather conditions are the key non-recurring sources of traffic congestion [36]. In the case of developing countries, there is a greater challenge to manage the sources of traffic congestion due to the variety of traffic mix, lack of compliance to lane discipline, presence of pedestrians in carriageway, and informal trading and parking on the street [17, 40]. [42] significantly contributed to research methodology by applying near-real-time data on speed measurements across an entire city to identify, quantify, and prioritize specific bottlenecks responsible for traffic congestion events in a metropolitan area. The thing that was interesting about this research was, they found a clear contradiction: the total amount of load spread across the traffic network stays relatively stable over time, but the specific places where traffic jams start change considerably from day to day. This kind of mega-level activity, which is based on macro-level stability, shows

TABLE 2.1: Causes, traffic flow impacts, and suggested mitigation measures for recurring congestion in Peshawar, Pakistan [7]

Cause		Impact on Traffic Flow	Supporting Evidence/Observation	Suggested Mitigation Measure	Frequency (%)
BRT corridor narrowing near stations	corridor narrowing near stations	Reduced lane width and bottleneck formation, particularly during peak hours	Field observations at Saddar and University Road show lane widths reduced to below 9 ft near BRT stations	Improve lane geometry, provide clear markings, and regulate parking around stations	85
Poor road surface and drainage conditions	road surface and drainage conditions	Vehicle slow-down and lateral movement due to potholes and water accumulation	Observed along multiple sections during rainy conditions causing intermittent stoppages	Regular maintenance and surface rehabilitation; upgrade drainage facilities	80
Insufficient designated parking spaces	Insufficient designated parking spaces	Vehicles occupy traffic lanes, reducing effective capacity	Noted near Amin Hotel and PC Hotel during business hours	Develop off-street parking and implement strict no-parking enforcement	78
Commercial and institutional activity concentration	Commercial and institutional activity concentration	High vehicle and pedestrian interaction leading to recurrent congestion	Heavy inflow observed near markets, hospitals, and universities along the 16 km corridor	Introduce time-based restrictions, pedestrian crossings, and coordinated signals	73
Absence of lane markings and signage	Absence of lane markings and signage	Disorganized movement, unsafe overtaking, and reduced throughput	Identified at Army Stadium and Jalil Kabab House intersections	Apply reflective markings, lane dividers, and modern traffic control devices	70
Improper location of police checkpoints	Improper location of police checkpoints	Artificial bottlenecks and queue build-ups during inspections	Queue formation observed near PC Hotel and University Road in peak periods	Relocate checkpoints to service lanes or wider sections	65
Encroachment and roadside vendors	Encroachment and roadside vendors	Reduced carriageway width and obstruction of traffic flow	Noted at Gulbahar and Firdous areas	Implement strict anti-encroachment measures and provide alternative vending zones	60
Weak enforcement and poor driver discipline	Weak enforcement and poor driver discipline	Frequent violations, lane changing, and wrong-side driving	Reported by survey respondents and supported by traffic police	Strengthen enforcement, awareness programs, and use automated monitoring	72

that static methods for dealing with congestion that focus on specific bottlenecks are likely to be ineffective. This means that near-real-time data is necessary to solve urban traffic problems. [7] studied the causes in traffic flow impacts and suggested the mitigation strategies for congestion in Peshawar, Pakistan as shown in Table 2.1.

2.1.1.2 Economic, Environmental and Safety Consequences

Traffic jams can have effects on the economy, the environment, and safety. The most apparent economic cost of traffic congestion is the lost value of the time of the commuter and the freight company. According to [5], congestion cost the US about 87 billion dollars a year in productivity losses. Also, traffic jams in the 25 most congested cities in the US could cost up to \$480 billion in losses over ten years [5]. Even though these numbers are for the US, they show how traffic jams affect the economies of other countries as well. Moreover, considering that freight and logistics are less developed in the developing world, the impact could be proportionally higher despite lower numbers on average [10].

The effects on the environment are equally severe. When cars are in stop-and-go mode instead of cruise mode, the fuel burns less efficiently, which means they use more fuel and release more pollution, like CO₂, CO, NO_x, and particulate matter, than they would do if they were in free flow conditions [36]. [39] showed this to become valid by measuring it. They found that the highest levels of pollutants are released into the environment during evening peak hours, and that CO emissions make up a large part of the total pollutants released because most of the vehicles that use the roundabout run on gasoline and compressed natural gas. In this context, it was discovered that emissions primarily occur during stop-and-go operations, worsened by factors such as illegal parking, inadequate vehicle coordination, and insufficient signal control. This finding supports other research that looks at how to manage traffic emissions and congestion at the same time. [17] did a quantitative study that showed how emission management and congestion management are related. They found that both channelization and optimal signal control reduced CO₂ emissions by 25% to 35% [17, 23, 36].

The safety of the roads is another element of the traffic problem that might not receive as much attention as the other two, which are time and pollution. [18] propose that almost 40% of all road accidents happen at intersections. There are about 2.5 million intersection-related accidents each year, and about 1.5 million of those involve left turns. Congestion increases the likelihood of rear-end collisions, angular accidents, and pedestrian incidents, particularly at uncontrolled

intersections and those with reversible queues that cause vehicles to be improperly positioned.

[43] claim that insufficient accuracy in modeling driver behavior during simulations (specifically, inadequate estimation of safety conflicts by traditional traffic models) may lead to a considerable poor evaluation of the potential safety implications of specific measures, such as signal timing optimization and speeding violations. They also obtained conflict reductions of 9.8% to 23% through their safety-oriented optimal velocity approach when enhanced signalization was implemented; otherwise, such an effect would remain undetectable without altering default simulation parameters.

2.1.1.3 Measurement and Quantification Methods

Prior to implementing any measures to address traffic jams, it is important to evaluate the problem. There have been a lot of studies on congestion, and each one looks at a different aspect of the problem. Speed-related measures compare the actual speed of travel on the road link to either a free-flowing speed or the posted speed. This gives the speed ratios that can be turned into the Travel Time Index and Planning Time Index. The volume-to-capacity ratio compares the amount of traffic to the most traffic that is capable of getting through. There are delay measures, which count the delays caused by congestion, and level-of-service grades, which turn combined measurements into descriptive categories that are easier to understand [6, 19].

[18] conducted a survey of all existing congestion parameters, applying each one to the same historical traffic data set to demonstrate that different parameters produce significantly varying results in characterizing congestion, despite utilizing identical data. They pointed out some benefits of certain indices. For example, speeds parameters were easy to collect and share, while delay parameters were more like what users actually experienced during congestion. Consequently, a universal congestion index does not exist, and the utilization of complementary indices developed to specific objectives is recommended [19]. Some common performance metrics used in microsimulation analyses are average vehicle delay, queue lengths,

throughput, and level of service. These are all easy to determine using simulation results [6, 17, 18, 29].

The use of GPS data from sensors in cars, smart phones, and other mobile devices has been an important advancement in measuring traffic congestion in the last few years. Researchers are able to examine congestion on a whole network level because of the data these technologies collect. This is much cheaper than putting in sensor equipment, which usually only covers a small area. [42, 44, 45] utilized GPS data to develop an algorithm capable of detecting congestion on a network-wide scale. This method was shown to be capable to find out about things like meso-dynamic bottlenecks that conventional point-based sensors wouldn't be able to observe.

2.2 Potential Solutions for Traffic Management Challenges

2.2.1 Signalized Intersection Analysis

Signalized intersections are the primary places where traffic jams, pollution, and accidents happen in city transportation systems. They are the root cause of the city's transportation problem. The effectiveness of signalized intersections is significantly influenced by the alignment of traffic signal attributes, including cycle duration, phase sequence, and green light ratio, with the varying traffic demand at each intersection movement, which fluctuates throughout the day and within specific time intervals [18, 29]. Microsimulation modeling is particularly suited for the analysis of signalized intersections due to its capacity to replicate individual traffic operations, including queue formation and disintegration, interactions among vehicle platoons released by successive traffic signals, and queue overflow from downstream intersections [41].

As an example of this potential, [6] used the VISSIM model to analyze the Rawalpindi intersection by simulating the current status and systematically changing the parameters that control signal timing until they got the most traffic flow and the least average delay. They noted that the existing signal timing strategy failed to

align with actual demand, a common issue in urban settings where signal parameters are determined through trial and error rather than comprehensive engineering analysis. They discovered that optimized timings significantly enhanced the level of service without necessitating alterations to the intersection's geometry. [29] developed to this methodology by examining not only nine alternative configurations of signal timing parameters but also various scenarios involving geometric modifications, including lane width adjustments, the introduction of a fourth operational phase, and the installation of a bridge structure at the analyzed European corridor intersection.

[18] showed in their methodological work on intersection modeling that computer vision can help make it easier to collect data for these kinds of studies. The authors used YOLOv5 to track and analyze videos, which let them automate counting turning movements, estimating the speeds of vehicles, and measuring the delays of pedestrians. The automated system, which was modified for local conditions, had a recall value of 0.62 and its counts of turning movements were very similar to those obtained manually. The authors established these automatically collected measures into a simulation conducted in SUMO and discovered that the ratio of vehicles executing left turns predicts the travel time at all approaches to intersections, yielding significant insights into optimal signal phase configurations under high left-turn demand scenarios. In a recent study by [30] that used both large language models and SUMO, they showed how to make traffic management plans for a corridor in Singapore without having to manually set all of the model parameters.

2.2.2 Performance Evaluation of Roundabouts under Multiple Traffic Scenarios

Roundabouts are an important part of how developing countries manage traffic. Roundabouts are widely used at intersections with moderate traffic congestion in developing countries because they are cheaper than full-scale signalization and can help reduce the number of right-angle accidents. However, research indicates that improperly designed and poorly maintained roundabouts perform worse than

their signalized equivalents, particularly regarding mixed traffic flows that result in traffic law violations [46].

For example, [39] executed a microsimulation study to see how well the Shibbari roundabout in Khulna, Bangladesh worked. Their study provides one of the most thorough assessments of roundabout performance regarding emissions production in a mixed traffic setting, typical of South Asian nations. They used calibrated emission models in the PTV VISSIM program to find out that the most polluted air is found in the roundabout's circulating part. This is because cars frequently slow down because of illegal parking, bad entry coordination, and a lack of traffic rules. The authors propose various enhancements, such as the implementation of lane markings, curbs, and the elimination of parking, as critical measures to enhance roundabout efficiency, even if signal control is introduced subsequently.

[24] examined roundabout optimization theoretically, introducing an analytical model designed to compute the ideal distance between a signal-controlled intersection and a downstream roundabout to reduce delays across the whole network. The model demonstrates that the optimal spacing between the signal-controlled platoon released from the signal-controlled intersection and the roundabout's entry control, based on yields, significantly influences network performance, a factor frequently neglected.

In another study, [27] used simulation models to solve an optimization problem for the network level in the city of Zagreb, Croatia. They evaluated the effectiveness of various alternative measures to enhance traffic flow within an actual urban network, utilizing multiple simulation models. They also demonstrate that simulation tools can be utilized to compare the efficiency of various intervention strategies, provided that the data collection protocol is consistent, which is fundamental to any comprehensive simulation study. The research methodology employed by [27] can serve as a reference point for researchers eager to conduct research at the network level, using real networks instead of synthetic geometries. Also, [15] provided a practical tool, in the form of a step-by-step guide, for the construction of a microsimulation in SUMO based on real-world data.

2.2.3 Impact of Heavy and Connected Vehicles on Traffic Operations

As more heavy vehicles and smart transportation systems are used, managing traffic has become more complicated, especially at intersections. This is where research is starting to focus on simulation. [25] propose a platoon-based optimization methodology for traffic signal management of heavy connected vehicles at urban intersections, executed through a VISSIM model utilizing data gathered in Tallahassee, Florida. This study obtains data regarding the present speed and location of each vehicle from connected cars to establish platoon formation and dynamically adjust the timing of traffic signals to ensure the arrival of heavy vehicles aligns with the green phase. The best results in terms of reduction in delays and stop counts were achieved at high connected vehicle density and over-saturation with the collaborative effect of platooning and adaptive control significantly outperforming either approach alone. [23] presented a study in Egypt by using SUMO-based traffic optimization. The study area is shown in Figure 2.2.

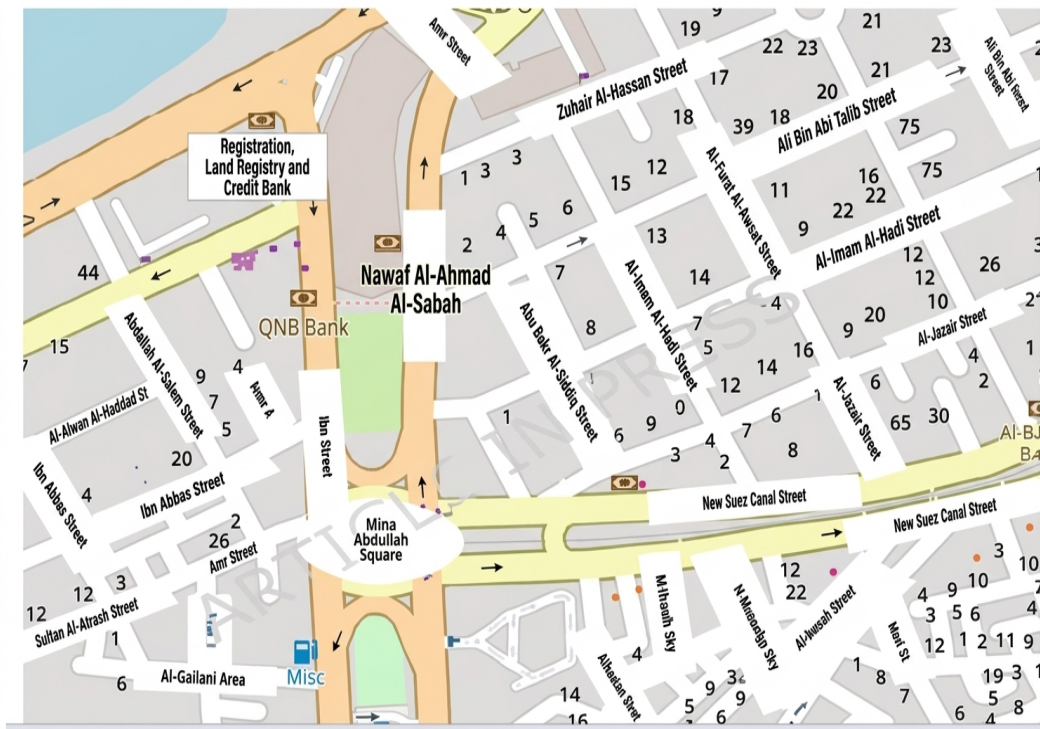


FIGURE 2.2: Study area representation (Umm Kulthum Square, Mansoura, Egypt) used in SUMO-based traffic signal optimisation study [23]

[47], on the other hand, emphasize the problem of tunnel traffic congestion in a SUMO-based simulation study to show how heavy vehicles are different from other types of vehicles. Because tunnels are closed and there are safety concerns about how they work, traffic signal control should focus on getting the most cars through while being aware of the higher risks. Their findings are, that speed restriction was more effective than road closure in managing accidents illustrates the necessity for application-specific calibration of the simulation tool to accurately represent real-world conditions.

The typical method to collect field data for building and testing a simulation model, which includes manual data collection, loop detection, and roadside cameras, is not only time-consuming and expensive, but it can also have policy issues when used at complicated multi-leg intersections. [48] demonstrated the utilization of drones for the collection of 162 road link data and traffic flow observation at five complex intersections in Salem, India, during peak hours. UAVs allow us to see from above, which means you can see the whole intersection's geometry and traffic flow at once. It provides the information about turns, how people queue, how pedestrians act, and how vehicles act that would take a lot of separate observations to get with traditional methods. The data collected from drones have been utilized in the construction of SUMO and AnyLogic simulations, with the consistency of results acting as built-in validation of their precision. Consequently, the authors proposed that traffic engineers and researchers from developing nations should take into account the utilization of aerial surveys as an effective and economical alternative to traditional methodologies, particularly in urban areas deficient in adequate sensor network infrastructure.

2.2.4 Signal Control Optimization: From Webster's Method to Deep Reinforcement Learning

2.2.4.1 Conventional Traffic Signal Optimization Methods

The practice of optimizing signal timings through engineering principles originated several decades ago with Webster's equation for determining the optimal signal

cycle time at a single-ended junction, which necessitates balancing fixed switching costs with variable delay costs based on the saturation ratio. Most of the last century, Webster's method and the use of TRANSYT and SCOOT to control traffic signals at multiple junctions were the most common ways to do so. They are still widely used at present [29]. The primary advantage of these models is the transparency and low complexity of their solutions; timings can be derived algebraically from empirical data without the necessity of simulation. Their main disadvantage is that they operate under the assumption of constant demand and cannot account for dynamic fluctuations in traffic flows [29, 46, 49].

[17] used Webster's model to find the most effective fixed-timed signal plans for a junction in Dhaka. This shows that using a classical approach to managing traffic lights can still lead to significant performance gains if it replaces a strategy that fails to perform well. The optimized plan caused delays of less than 40 seconds on average, kept the level of service stable, and cut emissions by 25 - 35% compared to the original traffic lights scenario. [29] also looked at optimizing signal plans as one of the nine scenarios in their case study using Aimsun software. They found that changing the timing of traffic lights could reduce some delays without changing the shape of the junction, but it was still not as effective as the most complicated restructuring methods. Figure 2.3 shows the Webster's signal phase diagram that illustrates cycle length calculation as well.

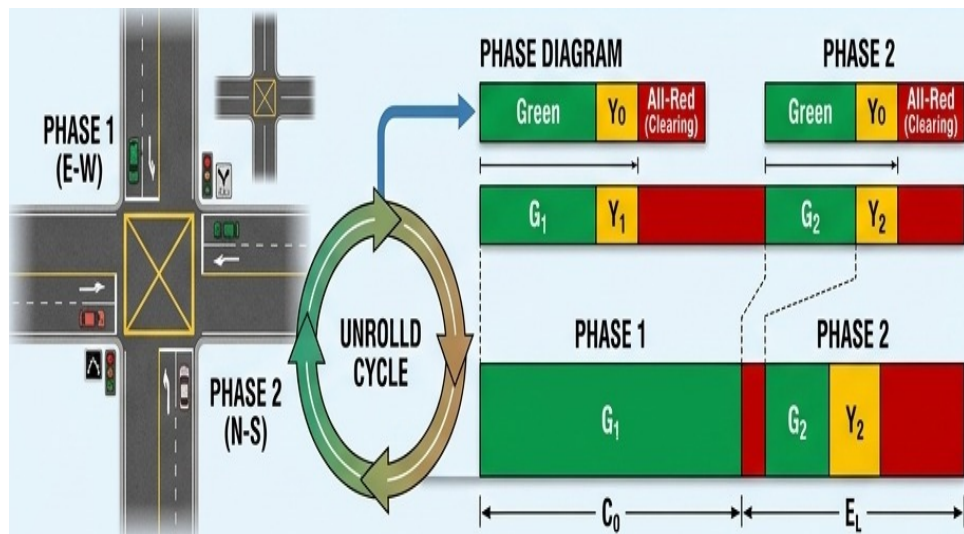


FIGURE 2.3: Webster's signal phase diagram illustrating cycle length calculation [29]

2.2.4.2 Adaptive and Actuated Signal Control

Automated signal control is the first step other than just fixed-time operation. It extends the green phase for a movement when sensors confirm that vehicles are still in the queue. More advanced adaptive systems, like SCATS, SCOOT, and ACS Lite, use real-time demand data to constantly change cycle lengths, phase breaks down, and offsets. This optimizes signal timings across the network to reduce the total delay for vehicles. These systems have shown big performance gains in cities with good infrastructure, but they can't be used everywhere because they need a lot of sensors and are hard to calibrate and maintain [49–51].

The rise of connected and self-driving car technologies is making it possible for a new generation of adaptive control methods that use vehicle-level data instead of gathered detector counts. In their study on platoon-based signal optimization, [25] showed how to use real-time connected vehicle data to find and prioritize heavy vehicle platoons at city intersections. The algorithm significantly reduced delays and stops by connecting signal timings with the actual arrival patterns of identified platoons. This was especially true in situations with a lot of connected vehicles and high demand.

2.2.4.3 Deep Reinforcement Learning for Signal Control

Deep reinforcement learning (DRL) has emerged in recent years as a transformative paradigm for adaptive signal control, offering the ability to learn optimal timing policies through interaction with simulated traffic environments without requiring an explicit mathematical model of the traffic system. In the DRL framework, a signal controller agent observes the current state of the intersection including queue lengths, vehicle waiting times, phase configuration and selects a signal action that transitions the system to a new state. The agent receives a reward signal that reflects the quality of the outcome and updates its policy to maximize cumulative reward over the episode. [46] performed a systematic investigation into the impact of state space definition on the learning efficiency and general applicability of a DRL-based signal controller trained within a SUMO environment. Their principal discovery was that supporting the state visualization with comprehensive data regarding vehicle queue lengths and waiting times rather than depending on

fundamental binary occupancy metrics that enables the DRL agent to acquire a more resilient policy that generalizes effectively to unique traffic situations without necessitating retraining. They compared their DQN-based model to a Soft Actor-Critic (SAC) baseline and found that the average delay per vehicle went down from 6.52 seconds to 5.13 seconds. This is a statistically significant improvement that shows how useful more informative state representations can be, even at the level of a single intersection.

[49] took a different approach by creating the Grouping-DQN (G-DQN) algorithm. This algorithm fixes two problems with the standard DQN framework: first, it can't accurately represent complex traffic conditions with the state definitions that are already out there, and second, the neural network takes too long to combine during training. G-DQN exceeded both standard DQN and the Advantage Actor-Critic (A2C) algorithm on all major performance metrics by grouping vehicles based on their wait time and lane position and using this grouped representation as the state input. Weibull-distributed vehicle generation in the SUMO simulation environment added some unpredictability to the demand, which made the results more believable in real life by better reflecting how traffic actually arrives.

[50] investigated the significant practical limitation that most urban areas lack the financial resources for extensive vehicle detection infrastructure, creating a Deep Q-Learning controller that functions effectively under partial detection situations where only a small number of vehicles is visible to the signal controller. Their reward function was set up to encourage minimizing delays even when not all the information is available. Their testing showed that the DRL controller still works better than fixed-time plans in situations where not all the information is available. This discovery substantially improves the practical use of DRL-based control by showing that full sensor coverage is not necessary for smart signal management.

2.2.5 Simulation-Based Assessment of Sustainable Transportation and Emissions

A developing section of a simulation literature clearly integrates traffic analysis within the overall framework of sustainable transportation, acknowledging that

congestion management is fundamentally linked to energy efficiency, greenhouse gas emission reduction, and enhancement of urban air quality. This integration is especially important in developing countries where the number of cars is growing quickly at the same time as the world is putting more pressure on them to cut carbon emissions and where air pollution in cities has serious health effects [5, 10, 36]. [6] clearly established microsimulation as a tool for assessing sustainable transport by using SUMO to look at emissions and fuel use as well as delays and service levels at the Rawalpindi intersection under both current and better conditions. Their framework shows that simulation-based sustainability assessment doesn't need any extra data collection beyond what is needed for regular performance analysis. This is because most modern simulation platforms can do emission modeling directly using immediate speed profiles made by the microscopic model. [39] used the same integrated method at the Khulna roundabout and found that the current layout causes carbon monoxide levels to rise well above acceptable levels during peak evening hours. They also found that making geometric changes can greatly cut down on both delays and emissions at the same time.

[38] expanded this analysis to the fuel consumption aspect, measuring the fuel wasted due to congestion at the Taxila Chowk intersection in Pakistan and utilizing this data to calculate the environmental cost of the existing operational inefficiency. Their finding that four out of five methods provide inadequate levels of service, along with the significant waste of fuel and emissions this results in, presents a strong economic and environmental case for the immediate adoption of traffic management strategies. [10, 52] supported this perspective in their systematic review, claiming that intelligent transport systems represent the most desirable approach for balancing the conflicting aims of mobility enhancement and sustainability in quickly urbanizing cities. The optimization literature reviewed in this chapter provides a range of intervention types, from low-cost regulatory measures requiring no physical infrastructure to full geometric reconstruction. Several studies suggest that these measures are best regarded as points on a single continuum of cost escalation, and that the benefit of a less expensive measure should be established before the merit of a more costly measure is considered. Table 2.2

brings together the improvement measures identified in the reviewed literature, their reported benefits, and the corresponding sources.

TABLE 2.2: Scenario improvement measures considered, with supporting literature, and basis for the S0-S4 selection

Optimization Strategy	Cost / Complexity Tier	Reported Benefits in the Literature	References
Parking management / enforcement	Low – enforcement only, no infrastructure	• Illegal parking identified as a direct constraint on the capacity gains achievable at a roundabout junction • Removing informal roadside obstruction found to be a prerequisite for realising the benefit of further signal or geometric intervention	[7, 27, 38, 39]
Fixed-time signal optimization (Webster-based)	Medium – signal infrastructure	• Delays reduced to under 40 seconds on average, with a stable resulting Level of Service, at a four-arm South Asian junction • Identified as the most extensively validated signal-timing method for mixed-traffic developing-country contexts	[17, 29, 47, 53, 54]
Actuated detector-based signal control	Medium-high – signal + detection infrastructure	• Consistently found to outperform fixed-time control under fluctuating demand by reducing unnecessary green time on under-saturated approaches • Identified as the natural next tier in the incremental deployment chain proposed for Pakistani urban intersections	[8, 33, 55–57]

Table 2.2: Continued from previous page

Optimization Strategy	Cost / Complexity Tier	Reported Benefits in the Literature	References
Approach-width and access management	Low-medium – regulatory / minor works, no signal infrastructure	• Absence of effective approach-width restriction identified as a contributing factor to congestion at a multi-leg unsignalized junction • Recommended alongside parking control as a low-cost, early-stage demand-management measure evaluated using a multi-criteria (entropy-TOPSIS) mitigation-technique comparison	[7]
Channelized turning lane / lane expansion	High – car-riageway / geometric modification	• Reduced average delay by approximately 20% and queue length by 15–20% at an unsignalized T-junction on a major expressway corridor • Reported benefit not isolated from any accompanying signal-timing or priority-rule change tested in the same study	[58]
Roundabout conversion	High – full geometric reconstruction	• Improved throughput by 10–15% and reduced delay at an unsignalized T-junction • Achievable benefit found, in a separate study, to be constrained by informal parking unless accompanied by enforcement	[58]; [38]

Table 2.2: Continued from previous page

Optimization Strategy	Cost / Complexity Tier	Reported Benefits in the Literature	References
Grade separation interchange reconstruction (overpass bridge structure)	Very high – full reconstruction	• Overpass configuration found to save the most travel time among nine tested geometric and signal-timing configurations at a busy European corridor node • Reported as markedly higher-cost than signal-timing optimisation alone, and not evaluated as a simulated scenario in the South Asian literature reviewed	[29]

2.3 Simulation Modeling as an Engineering Approach

2.3.1 Classification of Traffic Simulation Models

2.3.1.1 Macroscopic Models

Traffic flow models are typically placed into groups based on how much specific information they give about each vehicle and how they interact with each other. Macroscopic models, which are the most conceptual, interpret traffic flow as a wide range where the flow variables of interest mean flow rate, density, and space mean velocity that change according to conservation principles and empirical relations that are similar to those that govern compressible fluids [13, 26]. The Lighthill-Whitham-Richards (LWR) model is the most basic of all macroscopic models. The model illustrates the correlation between flow and density through the fundamental diagram and can anticipate the formation of shock waves. They also suggested that

adding a momentum equation to the basic model provides additional dynamical elements to it.

Macroscopic modeling can be performed quickly and easily on big networks; hence it is often used for planning transportation in cities. VISUM, TransCAD, and Emme are examples of software packages that use four-step travel demand modeling. This includes macroscopic traffic scheduling models and an algorithm that spreads OD flows through the network to help calculate cumulative measures. [13] state that these kinds of software applications work best for finding out how infrastructure and mode shift strategies affect the network as a whole. The only limitation of macroscopic analysis is its failure to incorporate individual driver behavior, intersection geometries, and signal phasing, which are essential for congestion analysis.

2.3.1.2 Mesoscopic Models

Mesoscopic modeling is in between microscopic and macroscopic modelling because it uses probability speed-density functions instead of car-following equations to describe individual vehicles as separate objects. Each vehicle is linked to a specific bundle or lane segment, and the speed of each vehicle is determined by the local density in that bundle, not by the distance between that vehicle and the next one. The mesoscopic model incorporates a certain level of individual variation, evident in microscopic simulations, while keeping computational advantages over a standard model. Consequently, the former can be regarded as the preferred model for corridor-level studies necessitating more precise results in contrast to macroscopic modelling [13, 26].

Aimsun is an application that you can acquire which lets you perform mesoscopic modeling and switch between different modelling resolutions. This feature is especially helpful for studies when the area of interest, like a busy intersection, needs to be looked at in the context of the whole region. The authors [29] utilized Aimsun's comprehensive microscopic modeling features to analyze scenarios for intersection enhancement. Aimsun's mesoscopic modeling option could still be very useful for further studying demand caused by it.

2.3.1.3 Microscopic Models

Microsimulation includes the individual modeling of each vehicle, with movement along both longitudinal and lateral dimensions specifically regulated by mathematically derived rules that simulate the behavioral characteristics of human drivers. In the microsimulation, each car has certain parameters, such as its desired speed, maximum acceleration and deceleration values, size, level of aggression as a driver, and gap acceptance. The cars' interactions with each other are calculated each second using models for following cars, changing lanes, and accepting gaps [12, 41]. This gives a clear picture of how traffic behaves, which lets you see things like queues forming and breaking up, disturbances spreading among groups of vehicles, the effects of timing schemes on certain types of cars, and safety-critical incidents [18, 29]. The comparison among macroscopic, mesoscopic, and microscopic simulation along with their characteristics is shown in Figure 2.4.

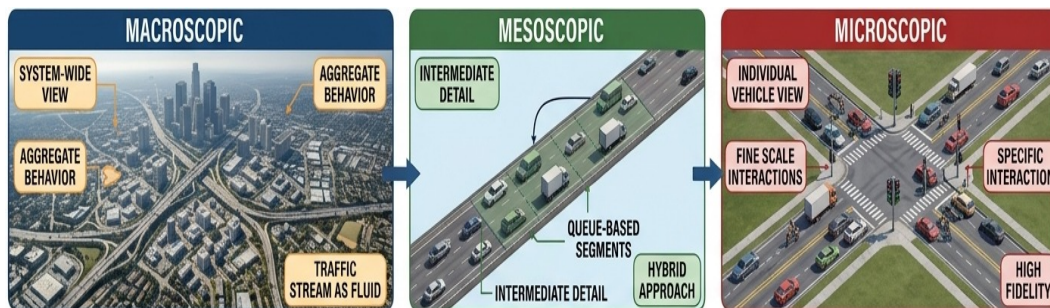


FIGURE 2.4: Macroscopic vs. Mesoscopic vs. Microscopic simulation characteristics [13, 26]

2.3.2 Microscopic Traffic Simulation Platforms: Capabilities and Applications

There are three practical reasons why simulation is preferred over purely analytical or field-trial methods for this class of problem:

- i. A new signal timing or geometric layout for a high-volume intersection like Kaak Bridge can be introduced at the intersection itself, but at a high cost and with the potential of disrupting traffic flow and endangering pedestrians and cyclists, and without the ability to test multiple competing designs and compare them prior to the physical change.

- ii. Secondly, closed-form analytical models like the Webster's equation have made assumptions of steady-state and homogeneous demand, which are not valid in the highly variable and mixed-vehicle conditions that prevail in traffic on the roads of Pakistan, whereas in microsimulation the demand to which the model applies can be described explicitly at the level of the individual vehicle.
- iii. Third, simulation produces a comprehensive performance history for each scenario tested, covering delay, queue length, speed, throughput and emissions; the result is a history that can be repeated, which makes it the kind of evidence base that transport authorities need to provide quantitative, comparable evidence to support an investment decision.

This is why this section highlights such a variety of microscopic simulation platforms that have become the preferred method of analysis for intersection level traffic research all over the world. [26] analyzed different simulation solutions based on diverse technical criteria and determined that microscopic simulation is the most appropriate method for analyzing intersection performance, signal control, pedestrian behavior, and mixed traffic flow. It was further determined that no universal platform exists for all situations, and that the optimal package can be selected based on the specific characteristics of the studied area, the vehicles that exist in the traffic flow, and the nature of the proposed intervention. [13] achieved equivalent results by evaluating ten existing packages, determining that VISSIM, Aimsun, and TransModeler possess the most characteristics related to intelligent transport systems and connected autonomous vehicles, whereas SUMO is unique among open-source alternatives.

2.3.2.1 PTV VISSIM

PTV VISSIM is a commercially available software program that uses time-stepping microscopic simulation to do stochastic traffic analysis. It has become the benchmark for analyzing traffic operations and conditions [13, 43]. The psycho-physical car-following model proposed by Wiedemann, which is based on the threshold

values for speed differences and spacing, is what each driver in VISSIM simulations uses to make decisions. Drivers are assumed to be in one of four states based on their values: free driving, approaching, following, or braking. The VISSIM software package is an essential for any organization or engineering company that works on transportation planning and operations analysis. It has a wide range of outputs metrics, impressive 3D visualizations, modules for public transit, pedestrian, and traffic signal control logic, and emission analyses. It also has an extensive track record of successful implementation [6].

[6] utilized VISSIM to analyze a severely congested intersection in Rawalpindi, Pakistan. They made a microsimulation model of the intersection based on information they got from the field about traffic volumes, traffic turning movements, and gap acceptance behaviors. They also looked at a few different scenarios for optimizing signal timing and managing traffic. The authors discovered that the level of congestion at urban intersections in Pakistan is quite high during their analysis. But even small changes to the timing of signals can lead to big drops in average delays, which makes the resources allocated to these kinds of improvements significantly.

[39] used VISSIM to simulate the roundabout in Khulna, Bangladesh. They calibrated the model using traffic and emission data that were collected at the same time but at different intervals during peak and off-peak hours. The results showed that the emissions from the roundabout's current setup are higher than what is acceptable during the busiest hour. Also, the roundabout's shape, illegal parking, and lack of coordination in the movement of cars make it impossible to make things better. So, using emission modeling in the same software as traffic simulation allows you evaluate both the operational and environmental benefits of the proposed measures.

The effectiveness of roundabouts can be improved by enhancing vehicle-following behavior at the roundabout through the implementation of an external optimal velocity car-following model created by [43] and integrated into VISSIM. This method allows us to get around the problems with the default Wiedemann 74

model of car-following. The authors used a new method for parameter calibration by getting trajectory data from roadside video reasoning and adjusting the model based on how drivers act on the road. Consequently, their methodology yielded enhanced accuracy in the replication of safety conflicts and more authentic evaluations of their mitigation through signal control and speed restrictions.

2.3.2.2 Aimsun, OmniTRANS and other Related Simulation Tool: A Comparative Overview

There are many simulation tools on the market, and SUMO and VISSIM are just two of them. Aimsun is an additional component of software that can do microscopic, mesoscopic, and macroscopic simulations all in one package. The Spanish company Transport Simulation Systems, S.L. made the software, which has been shown to work well for simulating complicated managed motorways, ramp metering schemes, and variable message signs. [29] used the Aimsun 8 package to simulate nine different plans for improving an intersection at a very busy traffic node on a major European road. They then compared the results of the simulations with the results of analytical computation based on the relevant technical rules. Their research showed that the overpass plan saved the most time, while optimizing the signal plan and adding four signal phases made smaller but still useful improvements at a much lower cost.

[59] utilized OmniTRANS to assess the impact of altering the operation of a two-lane inner ring road that surrounds the historical city center of Koice, Slovakia, from a bi-directional to a unidirectional traffic flow. The study investigated at how the changes in traffic intensity would affect both operating modes in the affected network. It also found parts of the network where the proposed change would lead to more demand than the current capacity can handle. So, simulation helped the planners reconsider the first idea and stopped possible expensive alterations. In this case, simulation is used to reduce risk. This is especially helpful when real-life experiments can't be done because of political reasons.

[48] implemented traffic simulations for five complex intersections in Salem, India, applying two methodologies: PTV VISSIM and AnyLogic, utilizing traffic data

acquired from unmanned aerial vehicle surveys. Using the same dataset, running simulations with two different software programs indirectly validated the model itself because both programs produced similar results. This case also shows how unmanned aerial technology can make it much easier and cheaper to collect data in the field. Beyond the range of car-following approaches described in the previous sections, simulation platforms also differ in licensing structure and in the level of programmatic access available to researchers seeking to automate calibration or run large numbers of scenario comparisons. These platforms are compared directly in Table 2.3.

TABLE 2.3: Microscopic simulation software comparison, with supporting literature, and basis for selecting SUMO

Software	Car-Following Model	Licensing	Capability / Limitation Reported in the Literature	References
SUMO	Krauss	Free, open-source	- Full Python/TraCI scripting access - reported as enabling per-vehicle-class calibration and automated multi-scenario batch execution not readily available in closed commercial platforms	[13–15, 17]; [60]
PTV VISSIM	Wiedemann 74/99	Commercial licence	Widely validated on comparable South Asian arterial junctions, but requires a paid licence, and its COM-based scripting interface is reported as less accessible for large-scale batch scenario automation than open-source alternatives	[58]; [6, 38]

Table 2.3: Continued from previous page

Software	Car-Following Model	Licensing	Capability / Limitation Reported in the Literature	References
AIMSUN	Gipps-based	Commercial licence	Effective for large managed-motorway and ramp-metering studies, but shares VISSIM's commercial-licensing barrier and has comparatively limited representation in the South Asian intersection literature reviewed	[29]; [60]
OmniTRANS	Network / mesoscopic-macroscopic oriented	Commercial licence	Effective for network-level, city-scale scenario testing, but not purpose-built for the fine-grained, vehicle-level behavioural detail required at a single mixed-traffic intersection	[52]
MATSim	Queue-based (agent simulation)	Free, open-source	Free and open-source like SUMO, but oriented toward large-scale, agent-based regional demand modelling rather than fine-grained, single-junction microsimulation	[60]

Table 2.3: Continued from previous page

Software	Car-Following Model	Licensing	Capability / Limitation Reported in the Literature	References
TransModeler	Cell-transmission / car-following hybrid	Commercial licence	- Identified, alongside VISSIM and Aimsun, as possessing the most ITS- and connected-autonomous-vehicle-related features among ten evaluated packages - Commercial licensing and CAV-feature specialisation reported as being of limited relevance to a conventional, non-connected-vehicle mixed-traffic junction study	[13]
Macroscopic platforms (VISUM, TransCAD, Emme)	Four-step travel-demand / network flow	Commercial licence	- Well suited to city-wide infrastructure and mode-shift planning using aggregate flow data - Unable to represent individual driver behaviour, intersection geometry, or signal phasing, and therefore reported as unsuitable for junction-level congestion analysis	[13, 26]

2.3.3 Car - Following and Driver Behavior Models

2.3.3.1 Theoretical Foundations

Car-following models are the most important part of the behavioral models that drive microscopic traffic simulation. This is because the speed and acceleration of each vehicle are based on how the vehicle in front of it is moving in the lane. The efficiency of car-following models is the most significant variable influencing the performance of microscopic traffic simulation, as it affects all subsequent analyses, including travel time, queue length, throughput, fuel consumption, emission levels, and the frequency of safety-related incidents [12]. In the past seventy years, many models for following cars have been produced. Some are based on very simple stimulus-response functions, while others are based on psychophysical theories and/or the study of real-world data [26].

The Gazis-Herman-Rothery (GHR) models, which were created in the late 1950s, are one of the most successful kinds of car-following models. They show the acceleration rate as a function of the ratio of the current speed to the speed of the vehicle in front of it. However, the GHR-type models have serious theoretical flaws. For example, they behave in ways that don't make sense in some parameter spaces. To solve these kinds of problems, the Gipps model was proposed in 1981 as a different way to do things. The Gipps model determines drivers' acceleration control using the safety constraint formulation, which means that drivers should slow down so they don't collide if the car in front of them suddenly stops [43].

2.3.3.2 Calibration Challenges in Heterogeneous Traffic

Calibrating car-following models is eventually more difficult in the heterogeneous traffic conditions common in the urban centers of South and Southeast Asia. While the Wiedemann psycho-physical car-following model included in VISSIM software and the widely used IDM model have been tested and validated against homogeneous traffic flows in Europe, characterized by strict lane discipline and consistent vehicle compositions, they tend to be unreliable when used as is to simulate heterogeneous traffic with significant shares of two-wheelers, three-wheelers, and overloaded trucks that ignore lane markings [17, 39, 61].

[43] specifically made an attempt to solve this problem by suggesting a safety-based version of OVM. This version focuses on modeling how the driver is likely to react to the perceived safety threats, which is different from the default model's threshold-based approach. The authors were able to change their behavioral assumption based on the traffic setting in question by calibrating their safety-based model against actual trajectories obtained through a real-time inference pipeline based on camera footage. The difference in safety conflict predictions between their enhanced safety model and the baseline Wiedemann model was significant, indicating that site-specific calibration should be regarded not only as an option but as an essential procedure for achieving realistic simulations in contexts where default model assumptions are inapplicable. Another study done in Dhaka confirmed this finding. [17] emphasized the need for this kind of calibration and tailored default SUMO model parameters to accurately represent the aggressive gap acceptance and lane-weaving behavior seen in Bangladeshi traffic.

2.4 SUMO - Simulation of Urban Mobility

The German Aerospace Center made the first version of SUMO (Simulation of Urban Mobility), a flexible, free, microscopic, and dynamic simulator for road traffic. A large group of international developers is now working on it [41]. This simulation tool can make complicated road networks and traffic scenarios. It can also model public transport schedules and communication between vehicles and infrastructure. It is capable of doing this with thousands of objects that represent different types of vehicles, like passenger cars, trucks, buses, motorcycles, bicycles, and pedestrians. One of the most important technical aspects of SUMO is its full Application Programming Interface which allows researchers use external controllers in the simulation to study intelligent transportation systems, reinforcement learning, and vehicle communications [30, 40, 47].

Multiple research studies have shown that SUMO is very useful for solving real-world traffic problems. For instance, [41] use SUMO to model a new Deep-Neuro-Fuzzy intelligent traffic management system in their article. The authors show that it is possible to combine the route assignment features of SUMO's built-in

routing algorithms (Dijkstra, A*, and CHW rapper algorithms) with external road weight calculations to create dynamic routing with an average accuracy of 98.63 percent. The framework of research methodology and geometry of intersection used in SUMO-based heterogenous traffic study by [17] is shown in Figure 2.5.

[18] also utilize SUMO effectively in a different study. They build and calibrate SUMO simulation models for signalized intersections in Las Vegas using data from a computer vision-based method of tracking vehicle trajectories. This study is unique because it uses a fully automated process to collect data. A deep visual tracker algorithm made just for tracking vehicle trajectories was used to look at video recordings of traffic moving through an intersection in order to make the SUMO model. This meant that data on turning movements for all traffic approaches were gathered automatically, without any help from people.

The analysis conducted in SUMO indicates that the left turn ratio is the only parameter that significantly influences travel time through an intersection, and that minor adjustments in signal timing may result in reduced delays, provided the model is correctly calibrated with data. Channelized intersections are intersections that have physical or painted islands to help direct vehicles into separate lanes so they have fewer places to conflict and/or fewer places to be confused. Non-channelized intersections are intersections where the entire junction surface is used for traffic, resulting in a greater number of conflict areas and a need for increased driver judgment. Figure 2.6 is demonstrates the SUMO network developed for channelized and non-channelized control strategies.

[53] demonstrated the adaptability of SUMO in evaluating emergency vehicle priority schemes on the congested arterial in Frankfurt. The process involved creating the origins-destinations matrix using the gravitational model, using OpenStreetMap data to build the traffic network, using traffic counts from the Frankfurt transport administration to calibrate, and comparing five signal precedence scenarios. All of the preceding schemes that were looked at worked to cut down on the travel time of emergency vehicles, which showed that they were useful for this kind of analysis. [47] adopted SUMO to study a specific case of tunnel traffic congestion. They created a micro-macroscopic hybrid traffic flow simulation model that was calibrated using measurements from the tunnel. Several scenarios were

Study Intersection

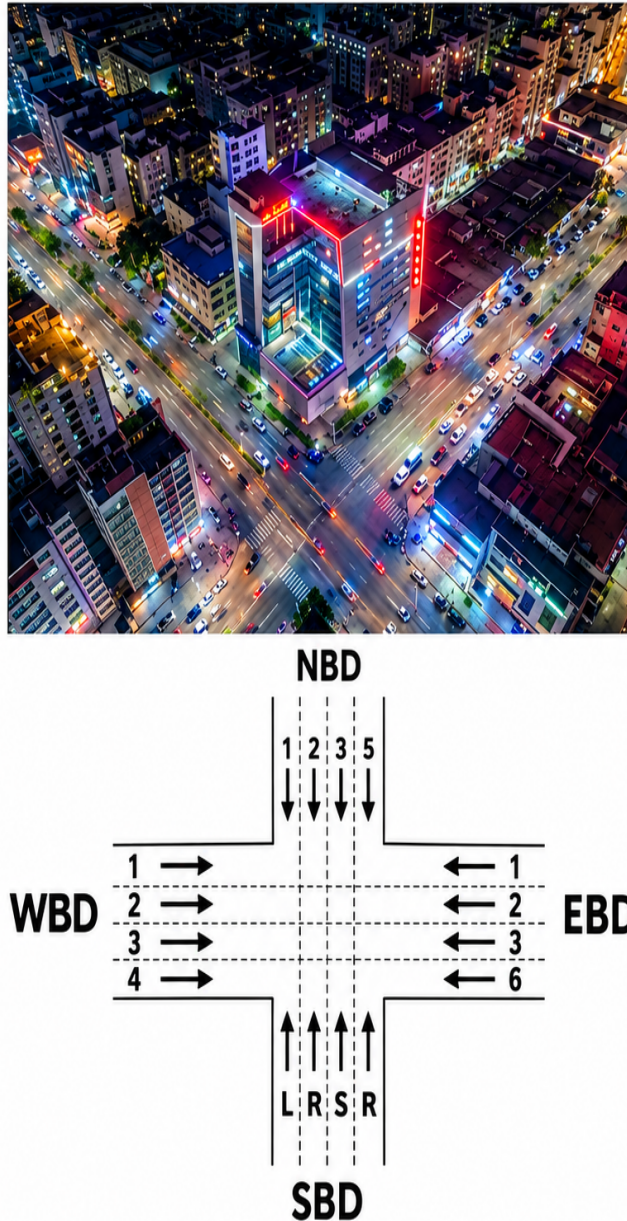


FIGURE 2.5: Research methodology framework and study intersection geometry used in a SUMO-based heterogeneous traffic study [17]

analyzed, and it was found that closing the entire road during an accident utilizes road capacity. On the other hand, selective speed limit policies work well to reduce traffic jams and queues without wasting road space in these situations.

The application of SUMO to the development of adaptive traffic control models

through large language model-based analysis was shown in the work of [30], who conducted the investigation in the congested Singapore road segment. The use of natural language processing to speed up the iterative process of generating scenarios, performing simulations, and making recommendations demonstrates the potential that artificial intelligence-based simulation holds for traffic management research. Researchers in traffic management can discover innovative methods to enhance the availability of simulations in regions lacking specialized skills through the integration of natural language user interfaces with simulation tools. [17, 48, 54, 62] showed that SUMO could simulate traffic and traffic control measures. They found that Webster's optimized signal timings and channelization of the road layout could reduce the delay time by more than 70% and emissions by 25% to 35% compared to manual police control methods. The study is also very important for managing traffic in Pakistan.

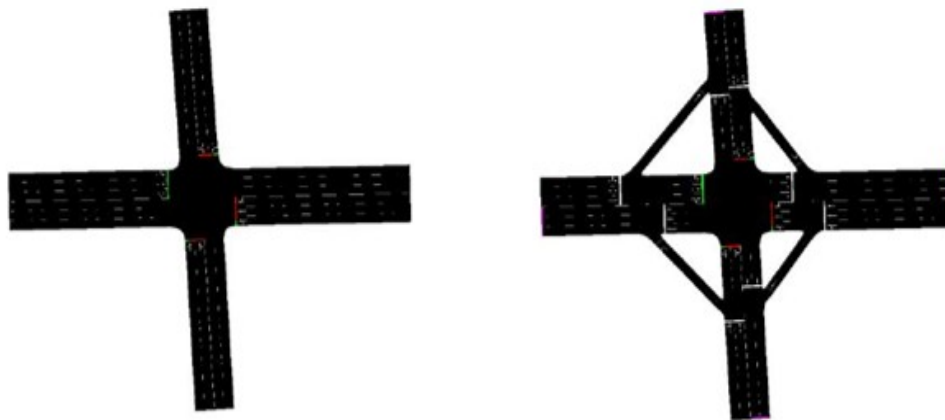


FIGURE 2.6: SUMO network development showing baseline (non-channelized) and channelized intersection control strategies [17]

2.4.1 Regional Review of Urban Traffic Simulation and Congestion Studies

2.4.1.1 Urban Traffic Congestion and Simulation Studies in Pakistan

Pakistan's major cities like Karachi, Lahore, Rawalpindi, and Islamabad represent traffic conditions that incorporate numerous challenging aspects identified in developing-country literature: diversified vehicle fleets with significant numbers

of motorcycles and three-wheelers, poor lane discipline, insufficient signal infrastructure, rapid population growth, and constrained institutional capacity for traffic management. Due to these circumstances, Pakistani cities are a particularly significant setting for simulation-based traffic research; however, the existing literature on this specific context is relatively limited [6, 38].

[6] directly addressed this gap by executing what seems to be one of the initial published VISSIM-based microsimulation studies of an intersection in Rawalpindi, Pakistan. The study site, marked by significant mixed traffic and frequent congestion, was generated using field data gathered during peak hours. The calibrated simulation was employed to assess the existing level of service and the potential for enhancement through signal timing optimization and intelligent management strategies. The research validated the relevance of microsimulation methodology to urban conditions in Pakistan and formulated a framework for subsequent intersection studies in the nation.

[38] used Aimsun to look at the Taxila Chowk intersection and found that it was very congested because of a lot of mixed traffic, poor signal management, and informal businesses taking up space on the road space. The study found that the H.M.C. road is the most likely to get stuck in traffic and measured the high costs of fuel and emissions caused by the current inefficiency. It also suggested a number of actions, such as installing signals, moving the market, and adding smart technology, and used simulation to show how well they would work together.

2.4.1.2 Urban Traffic Congestion and Simulation Studies in Asia

The traffic conditions in cities like Bangladesh and India are very similar to those in Pakistan. This makes them a great place to learn directly applicable methodological lessons. [17] executed the most extensive recent SUMO-based investigation of a South Asian intersection at a four-arm junction in Uttara, Dhaka, characterized by a manually controlled signal system that generates significant congestion and emissions during peak times. Their study development from field data collection through simulation calibration to multi-scenario optimization offers a comprehensive methodological framework that is directly applicable to intersection studies in Pakistan.

[39] examined the particular issue of roundabout performance within the Khulna Metropolitan area, where the Shibbari roundabout functions as a critical junction in the urban network yet suffers from unlawful parking, disorganized traffic flow, and pollution levels significantly exceeding safe limits. The traffic emission modeling technique they used in VISSIM shows how the environmental benefits of managing traffic jams can be measured in a single simulation framework. The suggestions for physical improvements they made based on the simulation can be used in other roundabout setups in South Asia.

[48] illustrated the effectiveness of drone-based data collection for Indian urban intersections, utilizing UAV footage to simultaneously survey multiple complicated junctions in Salem and integrating the resultant data into VISSIM and AnyLogic models. Their research demonstrates that researchers in developing countries are not limited to obsolete data collection techniques, and that advanced sensor technologies can significantly lower costs and enhance the quality of the field data essential for simulation models.

2.4.1.3 Urban Traffic Congestion and Simulation Studies in Southeast and Middle East

[30] researched adaptive traffic management in a congested roadway in Singapore, integrating SUMO with large language model-based AI to produce scenario recommendations and assess its effectiveness. Singapore's traffic infrastructure is much more advanced than that of cities in South Asia. However, the study's methodological contributions, especially the use of AI to help create and understand scenarios, can be used in many other places and could be adapted to places with fewer resources by using simpler language models or rule-based assistance systems.

[25] executed their study on heavy vehicle platooning and signal optimization at a Florida intersection. The research questions they address that how to mitigate the excessive delays faced by heavy vehicles at urban intersections under mixed traffic conditions, are directly applicable to Pakistani and South Asian cities where trucks and buses constitute a substantial portion of peak-hour traffic. Their discovery

that the platoon-based algorithm excels in scenarios with elevated connected vehicle penetration rates indicates a medium-term potential for its implementation in developing nations; however, the foundational signal optimization principles may be modified for non-connected settings utilizing traditional detection methods.

Four-leg signalized intersections are the widespread junction type in the literature and are common in cities with well-established signal-timing methods. And, the roundabouts, increasingly used in South Asian cities as an alternative to signalization, likewise dominate the literature and offer the broadest range of signal-timing interventions. Three-leg (T) unsignalized junctions, despite carrying comparably high volumes on major arterial corridors, appear far less frequently in the literature, as do four-leg unsignalised intersections, which are repeatedly identified as a source of severe congestion once unregulated. The outcomes reported in the preceding sections, together with their supporting literature, are summarized in Table 2.4.

TABLE 2.4: Intersection type comparison, with supporting literature, and basis for selecting an unsignalized T-junction

Junction Type	Typical Conflict Points	Reported Outcome in the Literature	References
Four-leg signalized	24–32	• Even small changes to signal timing produced large reductions in average delay at a congested Rawalpindi intersection	[6]
Roundabout / mini-roundabout	8	• Illegal parking and uncoordinated vehicle movement found to limit achievable improvement even after geometric optimisation • Geometric redesign reduced both delay and carbon-monoxide concentration simultaneously	[38]

Table 2.4: Continued from previous page

Junction Type	Typical Conflict Points	Reported Outcome in the Literature	References
Four-leg unsignalized	24–32	• Repeatedly identified as a primary driver of unacceptable Level of Service at South Asian arterial junctions • Informal roadside activity found to compound capacity loss beyond geometry alone	[10, 37, 63–65]
Three-leg (T) unsignalised	9	• Confirmed severe LOS F and delays exceeding 45 s/veh on the minor approach under real Pakistani mixed-traffic conditions • Lane expansion and priority-rule interventions reduced delay by 15–20%, without evaluating a staged low-to-high-cost signalization pathway	[58]
Multi-leg (five-approach) unsignalised junction	≈ 40–50	• Unacceptable Level of Service reported at four of five approaches, indicating that additional approach legs compound rather than merely adds to congestion severity • Operational failure attributed in part to the absence of effective approach-width and access-management control	[7, 37]

Table 2.4: Continued from previous page

Junction Type	Typical Conflict Points	Reported Outcome in the Literature	References
T-junction with ramp-transition	9, plus additional ramp-merge/weaving conflict	• Interchange-level congestion generally attributed to the superposition of arterial mainline through-movement, local commuter access, and converging ramp flow at a single point, a combination noted as being largely unaddressed by conventional intersection models	[6, 8, 20]

The closest example in the literature to a three-leg unsignalized arterial T-junction is an unsignalized T-junction at the southern end of the Islamabad Expressway (T-Chowk), analyzed using VISSIM microsimulation to assess improvements based on lane expansion, priority rules, and roundabout conversion, and to evaluate peak-hour operation and test these interventions [58]. That study reports severe LOS degradation and delays exceeding 45 seconds per vehicle on the minor approach of an unsignalized T-junction under Pakistani mixed-traffic conditions, and confirms that geometric lane expansion and priority-rule interventions can reduce delay by 15 - 20 percent. However, several elements of the intervention pathway investigated in that study are not addressed by the broader literature reviewed in this chapter. As noted in earlier work, conventional intersection models were designed primarily for basic at-grade junctions and do not adequately represent the specific dynamics of an interchange junction, where arterial mainline traffic, local commuter access, and a converging ramp stream must be coordinated at a single location [6, 8, 20]. The T-Chowk study is therefore not directly applicable to this interchange-type T-junction sub-category, in which all three traffic streams converge at an unsignalized point, nor is any other unsignalized T-junction study identified in the literature reviewed in this chapter, all of which are based on conventional at-grade geometries.

2.5 Summary

This chapter provided a thorough and critically organized evaluation of the literature concerning urban traffic congestion and microsimulation-based analysis, utilizing multiple papers from the current study's reference collection, along with essential methodological sources. The investigation has come to the following main conclusions:

- i. Traffic congestion is caused by a number of things, including urbanization, vehicular mobility, and land use patterns at the structural level. At the operational level, it is caused by intersection geometry, signal timing, and driver behavior. The effects are experienced in numerous domains, including the economy, the environment, and safety. In congested cities, the costs are in the tens of billions of dollars each year, and in South Asian cities, air pollution is a major health concern [5, 10, 19, 36, 37, 42].
- ii. Microsimulation is the most influential and flexible analytical tool for looking at traffic at the intersection level. It allows to investigate signal timing, geometric changes, and driver behavior under realistic stochastic conditions. SUMO and PTV VISSIM are the two most popular platforms, and each has its own strengths and weaknesses for different types of researches [13, 18, 26, 41].
- iii. The accuracy of microscopic simulation is highly dependent on the adaptation of car-following and driver behavior models to specific local conditions, particularly in diverse traffic scenarios where conventional model assumptions are not valid. Site-specific calibration utilizing field-measured vehicle directions is a methodological necessity for reliable safety and performance evaluation [12, 43, 52].
- iv. An organized system of signal control methods, from classical Webster-based optimization to adaptive and actuated control to deep reinforcement learning, gives better performance as the data and computing needs grow. Under realistic unpredictable demand conditions, DRL-based controllers have

shown to be better, and their usefulness in resource-limited city environments is increased by their ability to work under partial-detection constraints [46, 49, 50].

- v. The literature from South Asian cities especially Bangladesh, India, and the few studies from Pakistan shows how bad traffic is in the area and how sufficient funds can be made from using simulation-based intersection management. The emission and fuel consumption co-benefits of well-designed interventions, which have been shown to reduce emissions by 25-35 percent at individual junctions, are a strong case for including sustainability assessment in standard traffic engineering practice [6, 17, 38, 39].

The literature reviewed in this chapter corresponds closely to the field conditions observed at the site selected for the present study. The junction under investigation is an unsignalized, three-leg arterial junction that accommodates a heterogeneous vehicle stream, comprising motorcycles, cars, vans, buses, and trucks, a composition that mirrors precisely the mixed-traffic conditions motivating the car-following and driver-behavior calibration studies discussed earlier [12, 42, 51]. Its reliance on informal, manual police control in place of fixed signal infrastructure reflects the operational reality most frequently documented in the South Asian congestion literature examined in this chapter [6, 17, 37, 38], while the uncontrolled roadside parking observed along its approaches corresponds to the parking-related capacity losses reported at comparable junctions [38]. The site's sustained, high peak-hour demand on a major arterial corridor is consistent with the volume ranges reported at the most severely congested junctions discussed above, and its combination of unsignalized priority control with a transition-ramp geometry situates it within the specific, under-represented junction sub-category identified earlier in this chapter as a gap in the existing literature. Accordingly, each improvement measure and simulation-platform consideration reviewed in this chapter corresponds to an observable condition at the study site, rather than remaining a matter of general interest alone, and together these correspondences provide the methodological foundation for the site selection, calibration approach, and staged scenario framework developed in Chapter 3.

Chapter 3

Research Methodology

3.1 Background

As discussed in Chapter 2, traffic problems at urban intersections are widespread and a recurring issue in Pakistan and other developing countries due to which traffic simulation concepts and techniques for traffic analysis and optimization are required. And that SUMO-based microsimulation is the most suitable method to evaluate possible interventions under such conditions of traffic mix, which had not been used to estimate intersections similar to Kaak Bridge Intersection previously. This chapter explains a comprehensive methodology framework that has been implemented to study microscopic traffic congestion and evaluate optimization scenarios at Kaak Bridge Intersection as shown in Figure 3.1. The framework is both site-specific (based on the exact conditions at Kaak Bridge) and generic, since it can be used as an outline for similar police-controlled, un-signalized intersections in Pakistan and other developing countries. This method includes primary data collection, road network modeling, open-source microsimulation modeling (SUMO - Simulation of Urban Mobility), model calibration and independent model validation, and a systematic analysis of three optimization scenarios including signalization, parking management and adaptive signal control.

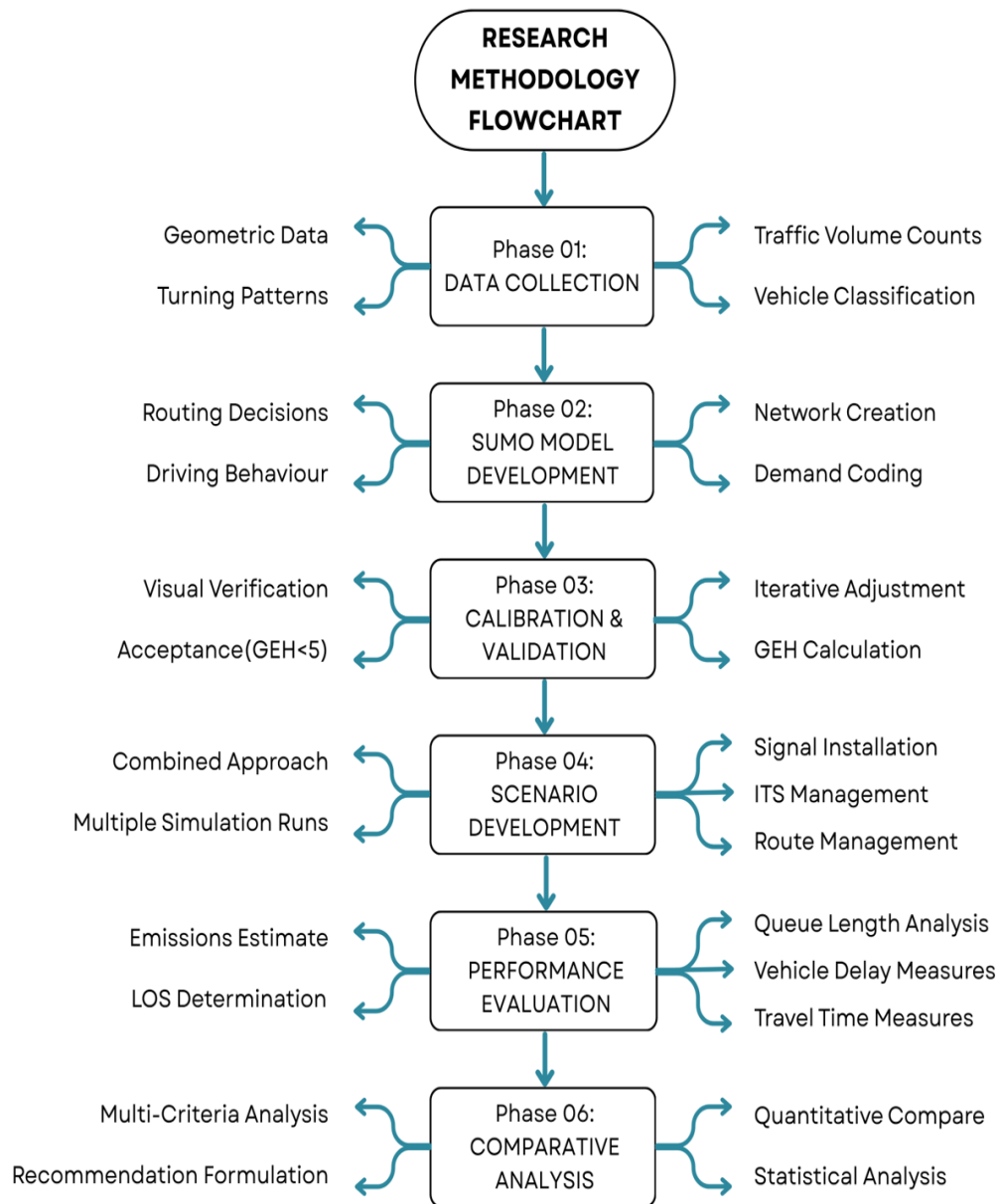


FIGURE 3.1: Overall Research Methodology Flowchart

Kaak Bridge Intersection is located on the Kahuta road along the Islamabad Expressway, one of the busiest main arterial roads of the area and is at present controlled with police and manually operated with no traffic-signals installed. The traffic is highly variable, comprising motorcycles, private vehicles, light commercial vehicles, minibuses, and heavy trucks, all flowing together without any lane discipline. This scenario is a representation of a significant number of intersections in Pakistan and other South Asian cities [6, 20, 28, 38]. There are no signaling, variation and growth in Islamabad's vehicle population that causes serious and

increasing congestion with measurable economic, environmental and safety costs to traffic users on a daily basis [7, 10, 33].

SUMO is open-source, mitigating the software expenses that limit simulation research in Pakistani institutes. It has a vehicle-type structure that allows the addition of auto-rickshaw and motorcycle categories that are not supported by commercial tools. Its TraCI Python Application Programming Interface (API) allows the evaluation of dynamic signal control and a growing number of published SUMO studies in South Asian varying traffic provides calibration guidance. This study contributes to the body of work by presenting SUMO based microsimulation of a Pakistani un-signalized intersection - a context that has received little attention in simulation despite being the typical operating mode for hundreds of congested urban intersections in Pakistan [17, 40, 61, 66].

The study follows a quantitative, simulation-based case-study procedure and conducts a before-and-after analysis. The three improvement scenarios are compared to the initial level (police-controlled) SUMO model of the intersection calibrated and validated against local traffic data. The methodology complies with the methodology of similar Pakistani and South Asian congestion studies [6, 23, 28] and is also in accordance with best practice for microscopic simulation-based transport research across the globe [12, 17, 29].

The research methodology is logical, in those existing concepts of traffic flow, car-following and traffic signal control are transformed into a SUMO model, which is calibrated against local field observations, and this model provides quantitative evidence of performance for the various scenarios. The framework includes a critical recalibration feedback loop where if the model does not satisfy validation thresholds, calibration parameters are systematically changed and the simulation is re-run until an acceptable agreement with field observations is achieved [12, 15, 43].

It is a regular quality-control method in microsimulation, and it is highly recommended for SUMO scenario construction [15, 66]. The Pakistan-specificity of the study is retained throughout all the stages of the methodology. PCU conversion factors, vehicle-class parameter initialization, driver-behavior sigma values and junction logic are all based on conditions observed at Pakistani or identical

South Asian sites, rather than the default values calibrated in European or North American settings where traffic homogeneity and lane discipline are fundamentally different from what is observed at Kaak Bridge. The key methodological point of variation, which differentiates the present study from generic simulation, is the focus on the local context, which makes the conclusions of the study useful to Pakistani transport planners and policymakers [43, 67–69].

3.2 Study Area Description

3.2.1 Kaak Bridge Intersection - Key Characteristics

The study has been carried out in Islamabad, the Federal Capital of Pakistan where the population has grown from less than one million at the time of the city's emergence to over two million in the Islamabad Capital Territory and over four million in the extended Rawalpindi-Islamabad metropolitan region. The constant congestion on the city's principal arterial corridors during peak hours has been the result of rapid urbanization of Islamabad along with a vehicle registration growth rate which has consistently been higher than the road network expansion [10, 70]. The Islamabad expressway is one of the most critical among these corridors providing a primary arterial for commuters, freight and intercity traffic between Rawalpindi, the major city areas and the outer regions of the capital. Traffic conditions on the expressway are representative of a varied category of Pakistani urban arterials, making the study findings generalizable across a substantial geographic scope [33, 71]. The study intersection is located on the Rawalpindi-Kahuta Road, also known as "Kahuta Road," near Kaak Bridge in Sihala, Islamabad Capital Territory (ICT). This road is part of the N-39 national highway extending from Kaak Bridge to Kahuta under the jurisdiction of the National Highway Authority (NHA), while the stretch in the immediate vicinity of Kaak Bridge falls within the territorial jurisdiction of the Islamabad Capital Territory (ICT). This area was selected for this study because it is known for having a lot of traffic and congestion during rush hour.

Kaak Bridge Intersection was selected for this research based on critical-case selection logic, where a phenomenon under investigation is to be observed and analyzed.

It is most clearly observed where the conditions giving rise to it are most extreme. This approach is consistent with the case-selection strategies discussed by Flyvbjerg (2006) in his analysis of case selection in applied research. Kaak Bridge Intersection satisfies this description in several respects. It lies on a major road that carries heavy traffic volumes and serves as a key route for the movement of goods and people. It is not a minor road but forms part of the Islamabad Expressway, a major arterial route of substantial economic and commuter importance, and it operates without any fixed signal infrastructure. The combination of sustained high-volume traffic and an active minor-approach conflict at an unsignalized T-junction represents precisely the concentrated, least forgiving form of intersection conflict described above. This ensures that any pattern identified, and any improvement evaluated, in this thesis is tested under the most demanding conditions to which it will be applied, so that any resulting recommendation has a realistic implementation pathway rather than being based on an idealized or best-case operating environment.

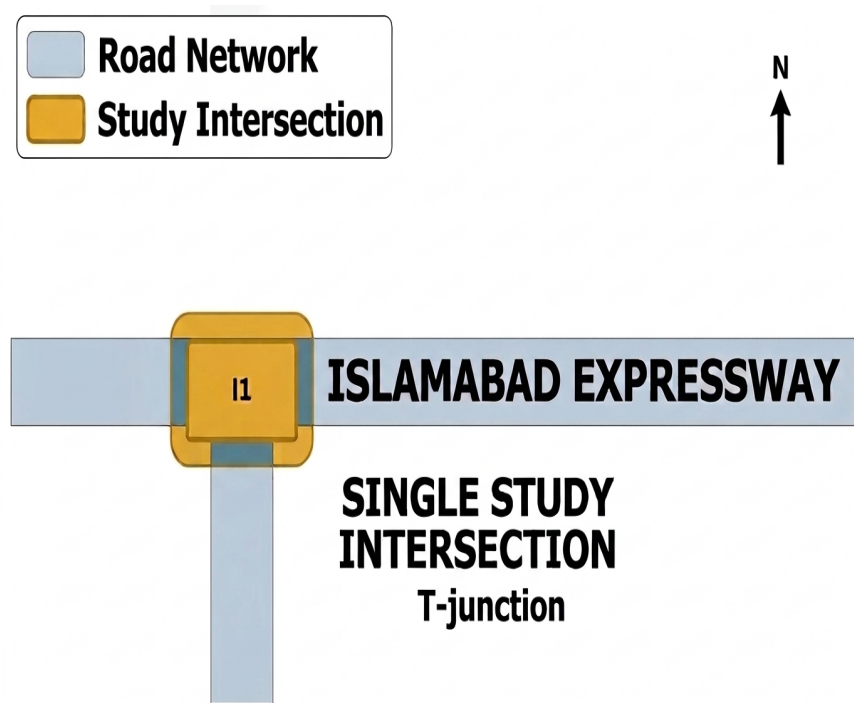


FIGURE 3.2: Schematic Plan: Kaak Bridge Study Area Network (Islamabad Expressway)

Kaak Bridge Intersection is a three-arm junction (as shown in Figure 3.2) located on Kahuta road along the Islamabad Expressway where the highway crosses a

major local collector road. The intersection is currently under police and manual control with no traffic signal devices installed. During rush hours, traffic officers stationed at the junction manually control traffic movement (see Figure 3.3), but because there is no fixed signal infrastructure, off-peak and late-night traffic is unregulated.



FIGURE 3.3: Manual traffic control and police-directed flow management at the Kaak Bridge Intersection during peak hours

The main types of vehicles found during reconnaissance surveys are motorcycles, passenger cars, passenger vans, buses, and heavy goods vehicles. Motorcycles and passenger cars account for a significant percentage of the total flow. This analysis is consistent with the reported conditions at other major Pakistani urban intersections [6, 28, 38]. Queue formation on all three approaches during the morning and evening peak periods was observed to be severe, with queue lengths extending several hundred metres upstream on the expressway legs and blocking the entry of the secondary road.

3.3 Field Traffic Data Collection

A detailed primary data collection method is carried out at the study intersection to acquire all the inputs required for building, calibrating, and validating the SUMO microsimulation model (see Table 3.1). The method covers a full indicative weekday (07:00-18:00 hours) from the morning peak (approximately 07:00-09:30),

the midday off-peak (09:30-16:30) and the evening peak (16:30-18:00) in one continuous session. Full day collection is important for generating periodic demand variation profiles needed for realistic SUMO simulations as well as ensuring that the simulated change between congested and free flow conditions are consistent with the field observations [5, 19, 39]. The site is being observed simultaneously, the turning movements, and queue formation areas were observed. Figure 3.4 illustrates the complete data collection framework.

TABLE 3.1: Geometric and Operational Characteristics of Study Intersections

Parameter	Kaak Bridge Intersection
Junction type	Three-arm (T-junction)
Current traffic control	Police / manual control only
Number of approaches	3
Lanes - expressway approaches	1 lane each direction
Lanes - cross/minor road	1 lane each direction
Posted speed limit	60 km/h
Pedestrian crossings	Informal / uncontrolled
Median barrier	No
Observed peak-hour LOS (est.)	E - F (near capacity)
Dominant vehicle types	Motorcycle, Car, Truck, Bus, Van

3.3.1 Classified Traffic Volume Counts

The counts of classified traffic volume are carried out at 60-minute intervals over the observation period. All vehicles passing each approach are manually counted and recorded in one of five classes: motorcycles (MC), passenger cars (PC), passenger vans, buses and heavy goods vehicles like trucks (HGV). The five-class scheme covers the entire spectrum of vehicle types at Kaak Bridge and is consistent with the classification schemes employed in comparable developing countries intersection studies [4, 6, 17]. All raw counts are subsequently be converted to Passenger Car Units using the equivalence factors in Table 3.2.

The procedures adopted for data collection are consistent with established practice in transportation engineering field surveys. The continuous, video-verified manual classified counts conducted during the morning peak, midday off-peak, and evening

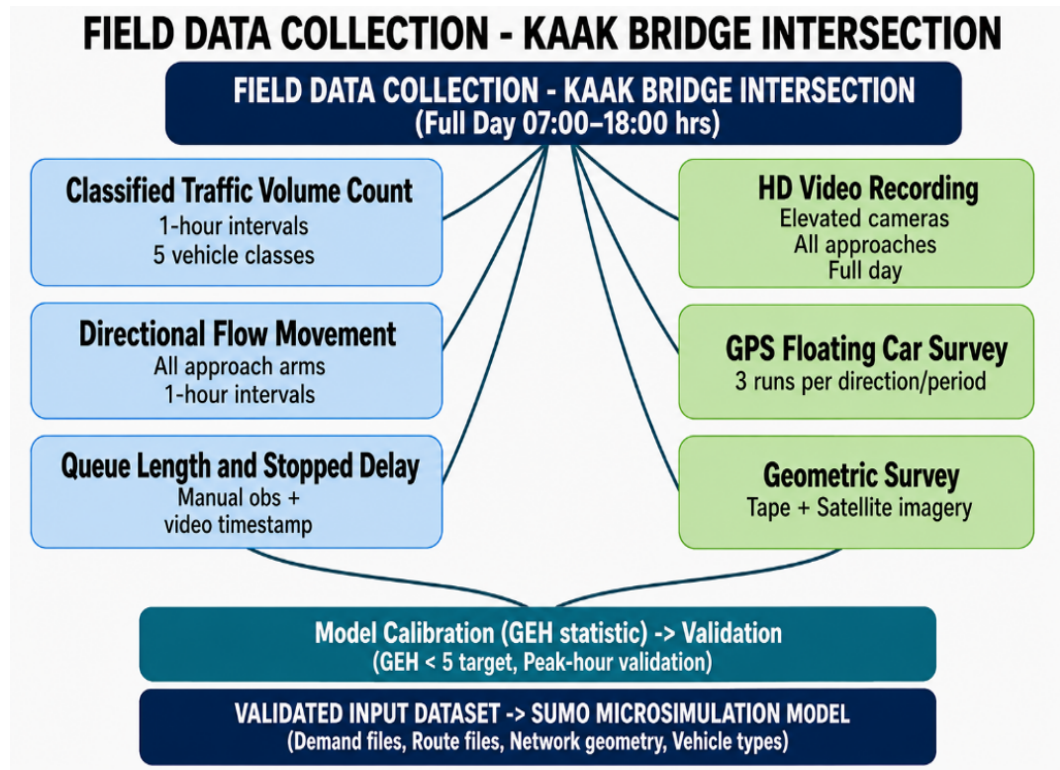


FIGURE 3.4: Field Data Collection Framework

TABLE 3.2: Passenger Car Unit (PCU) Equivalence Factors

Vehicle Category	Code	PCU Factor	Reference Basis
Motorcycle / Scooter	MC	0.50	Pakistan Roads Manual; [17]
Passenger Car	PC	1.00	HCM 7th ed. (2022) - baseline unit
Light Commercial Vehicle	LCV	1.50	Pakistan Roads Manual; [4]
Minibus / Van	MB	2.00	[6]; IRC: 64-1990
Heavy Goods Vehicle / Truck	HGV	3.00	HCM (2022); [17]

peak periods follow the FHWA Traffic Monitoring Guide [72], which specifies a 15-minute-to-hourly, manual or video-based classified count as the standard method for characterizing a representative day of traffic, using the five-class vehicle scheme shown in Table 3.2. The classified volume counts, directional flow counts, spot-speed studies, and delay studies were conducted in conjunction with one another, following the standard procedures described in the ITE Manual of Transportation

Engineering Studies [73]. The directional-distribution (D) factor and peak-hour (K) factor used in the demand-profile analysis in Figure 3.11 are based on the AASHTO Policy on Geometric Design of Highways and Streets (AASHTO Green Book) [74].

In this study, trucks and buses are each treated as a single, non-subdivided vehicle type, without further disaggregation by axle configuration. This is a standard and readily replicable practice in South Asian heterogeneous-traffic and SUMO-calibration research. Detailed vehicle classification is essential for traffic-flow and microsimulation studies due to variations in vehicle length, acceleration, and space occupancy. Conversely, axle-level detail is primarily needed for pavement and structural design, where ESAL calculations depend on axle loads. Consistent with this approach, Zeb et al. [75] defined single, undivided categories for Buses and Pickup Trucks among the nine simulated vehicle types in their heterogeneous traffic simulator, which was validated using field data from Peshawar, Pakistan. Similarly, Choudhury et al. [76] recorded Bus and Truck as undivided categories in their SUMO study of Khulna, Bangladesh. Furthermore, the National Highway Authority [77] records Car, Van, Bus, and Truck as single, non-subdivided vehicle categories in its national Vehicle Operating Cost study for Pakistan. Figure 3.5 illustrates the vehicle-class composition of classified traffic counts of all five vehicle classes, being observed at the respective Kaak Bridge Intersection.

The directional flow is recorded in parallel with volume at each approach at 60-minute intervals throughout the entire observation period. The Directional Distribution factor from the AASHTO Green Book [74] was used to account for the directional flow of traffic (i.e., East In versus West In) along the same expressway through-route at Kaak Bridge. The minor stem of the T-junction (South In) does not form part of this directional pair and is reported as a separate approach volume. The directional flow data is the primary source to create the source-destination matrix from which SUMO vehicle routes are created with the dual-router function, and the data are used in the calibration phase to ensure that the simulated turning proportions agree with the observed values in the field [15,18]. The police-controlled Kaak Bridge site focuses on recording any irregular movements, such

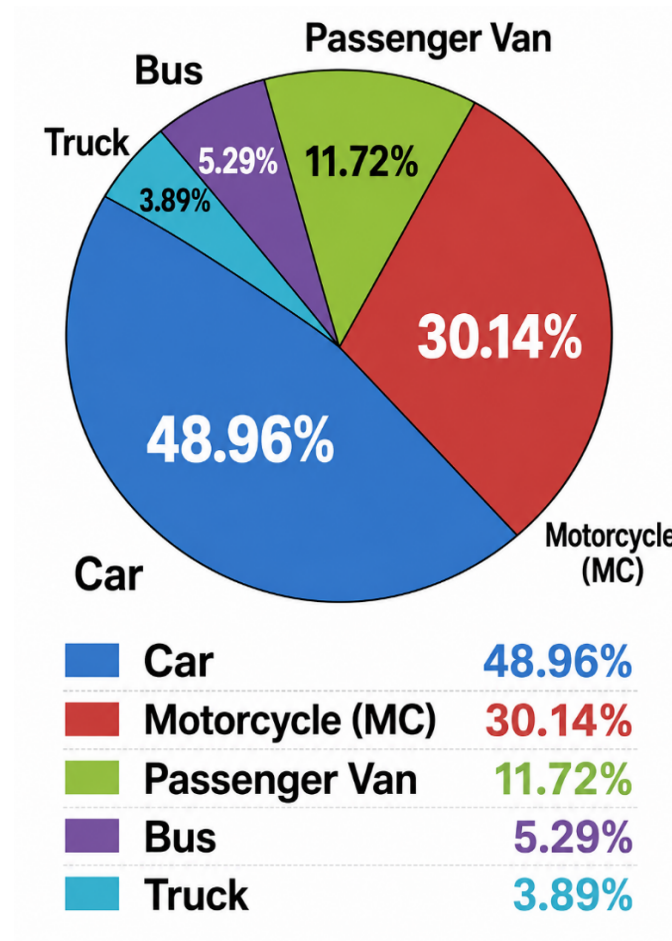


FIGURE 3.5: Vehicle-class Composition of Classified Traffic Counts

as U-turns unauthorized roadside passenger drop-offs, and irregular lane changes, which the lack of signal control enables and which must be represented in the SUMO model (as illustrated in Figures 3.6).

An instrumented vehicle equipped with a GPS and driven by a skilled observer has been used to collect travel-time and speed data along the whole study path. A minimum of three runs per direction have been made for each observation period to obtain GPS tracks from which the vehicle position, instantaneous speed and acceleration are determined on a second-by-second basis. The GPS records are used for two purposes; as independent travel time observations to verify the outputs of the SUMO model, and the instantaneous speed profiles are used to calibrate the Krauss car-following parameters, mainly the sigma (driver imperfection) factor, the desired time headway (tau) and the minimum gap distance [12, 43]. The



FIGURE 3.6: Mixed and heterogeneous traffic composition illustrating heavy transport vehicles (HTVs) interacting with commuter traffic at the connecting approach.

floating-car methodology used here follows that applied by [70] in their macroscopic travel-time study of the Islamabad road network and is consistent with the GPS-based validation approach adopted in recent Pakistani simulation studies. The GPS floating car speed distance profile is shown in Figure 3.7.

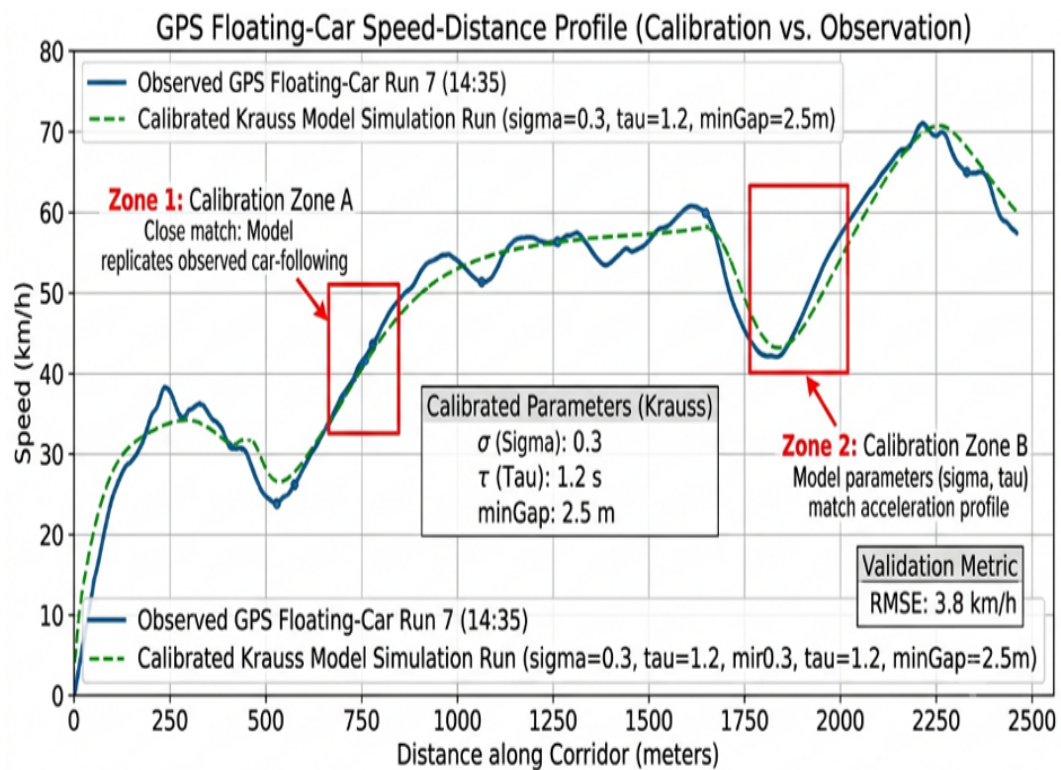


FIGURE 3.7: GPS Floating Car Speed-distance Profile

3.3.2 Queue Length and Stopped-Delay Observations

Maximum queue lengths have been manually recorded at the intersection approach during both peak times by counting vehicles in queue at the start of each green interval (or at the point when police officers signal a discharge). The delay per stop per vehicle were estimated from video footage by tracking a random sample from the time they form the queue until they clear the stop line, measuring the duration of the waiting time with a stopwatch or video recording. The roadside bottlenecks and capacity reduction caused by unauthorized vehicles at irregular parking that causes the queue formation is shown in Figure 3.8.



FIGURE 3.8: Roadside bottlenecks induced by unauthorized passenger vehicle drop-offs.

These measurements operate as the baseline performance metrics with which the SUMO delay and queue outputs are validated, and also act as direct measures of current congestion severity providing context to the scope for improvement of each scenario [7, 23, 29].

3.3.3 Geometric Survey

A comprehensive geometric survey of intersection was performed using steel measuring tapes, a GPS meter, and Google Earth high resolution satellite imagery (see Figure 3.9). Recorded parameters include lane widths on all approaches, approach leg lengths, pedestrian crossing widths and positions, kerb and island positions and any channelization features. Accurate geometry is critical for the correct building

of the SUMO netedit network model: incorrect lane widths directly affect simulated vehicle interactions and queue discharge rates, [15, 61]. The survey has also recorded the positions of any informal obstructions such as street vendors, parked vehicles, and encroachments, that reduced the functional carriageway width available to moving traffic, as these must be accounted for in the effective lane width parameters of the SUMO model. Table 3.3 provides the summary of field data collection methodology that has been executed.



FIGURE 3.9: Satellite Image of Kaak Bridge Intersection

Three measures were taken to ensure the reliability of the field data collected. First, all classified counts at this busy and complex site were tallied from the video recordings, and a sample of the video-derived tallies was independently re-checked by a second review of the corresponding footage, following the video-based quality-assurance approach recommended for classified counts in the FHWA Traffic Monitoring Guide, as described in Section 3.3.2. Second, rather than relying on a single, one-off count, the standard procedures of the ITE Manual of Transportation Engineering Studies call for multi-day, multi-period (morning, midday, and evening) sampling to obtain a representative, rather than anomalous, picture of site conditions. Third, further evidence of this reliability is provided independently of the downstream validation: the network-level GEH statistic comparison shows agreement between the field data and the independently developed SUMO simulation to within a GEH of 5.0.

TABLE 3.3: Summary of Field Data Collection Programme

Data Type	Method	Duration / Frequency	Use in SUMO Model
Classified traffic volumes	Video recording + Manual count extraction	Full day 07:00 - 18:00, 60-min intervals	Time-varying demand profiles; PCU flows
GPS travel time / speed	Floating-car GPS survey	Min. 3 runs/direction/period	Calibration and travel-time validation
Queue lengths	Manual observation + video	Peak periods	Queue-output validation per approach
Stopped delay	Video time-stamping	Min. 30 vehicles/approach, peaks	Delay output validation per approach
Police-control intervals	Manual timing by stopwatch	Peak periods, continuous record	Baseline priority - control logic in SUMO
Geometric survey	Measuring Tape + satellite imagery	Single full-day visit	netedit network construction

The field data reported in this chapter, comprising directional classified traffic volume counts (East In, West In, South In), GPS floating-car speed runs, queue-length observations, and stopped-delay timings, were collected in person at the Kaak Bridge Intersection site. Few Field Tally Sheets are provided as a sample in Appendix A.

3.4 SUMO Model Development

3.4.1 Road Network Modeling

The road network model is built in netedit, SUMO's graphical network editor. First, the structure is extracted from the OpenStreetMap (OSM) data using the netconvert command line tool. The imported network is then opened in netedit

and corrected systematically to comply with the geometric dimensions, lane configurations, turning restrictions and approach lengths recorded in the field survey, as shown in Figure 3.10. All highway approaches maintain a minimum approach length of 600 metres upstream of the assumed stop position so that queues are able to grow and dissipate within the network boundary under the most congested demand scenarios preventing artificial interruptions that would affect queue length and delay outputs [6, 50, 53, 59, 78].

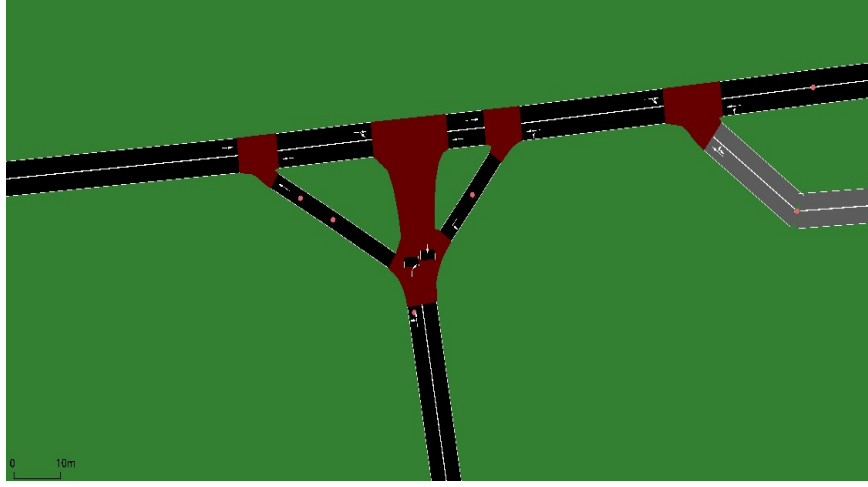


FIGURE 3.10: Constructed Kaak Bridge Intersection SUMO Network in netedit

3.4.2 Traffic Demand Specification

The demand of vehicles is defined by a set of specified flow definitions in XML, each of which has the vehicle type, departure-time distribution, origin edge and destination edge. The 60-minute interval PCU-equivalent traffic counts are converted to identified flows for each vehicle class and assigned to the correct OD pair in the corridor. The time varying flow rates from 07:00 to 18:00 span the entire periodic demand cycle from the morning peak, through the midday off-peak, to the evening peak. The Dua router tool takes the OD matrix and typed flow definitions and produces vehicle route files (rou.xml) where each vehicle is assigned a specific departure time and route. Random departure-time disturbance is introduced within each 60-minute time slot using SUMO's built-in random seed

functionality to avoid unrealistic uniform platoon releases [17, 79]. The traffic demand that is collected during the field survey and is being used in SUMO network building for different time intervals is shown in Figure 3.11.

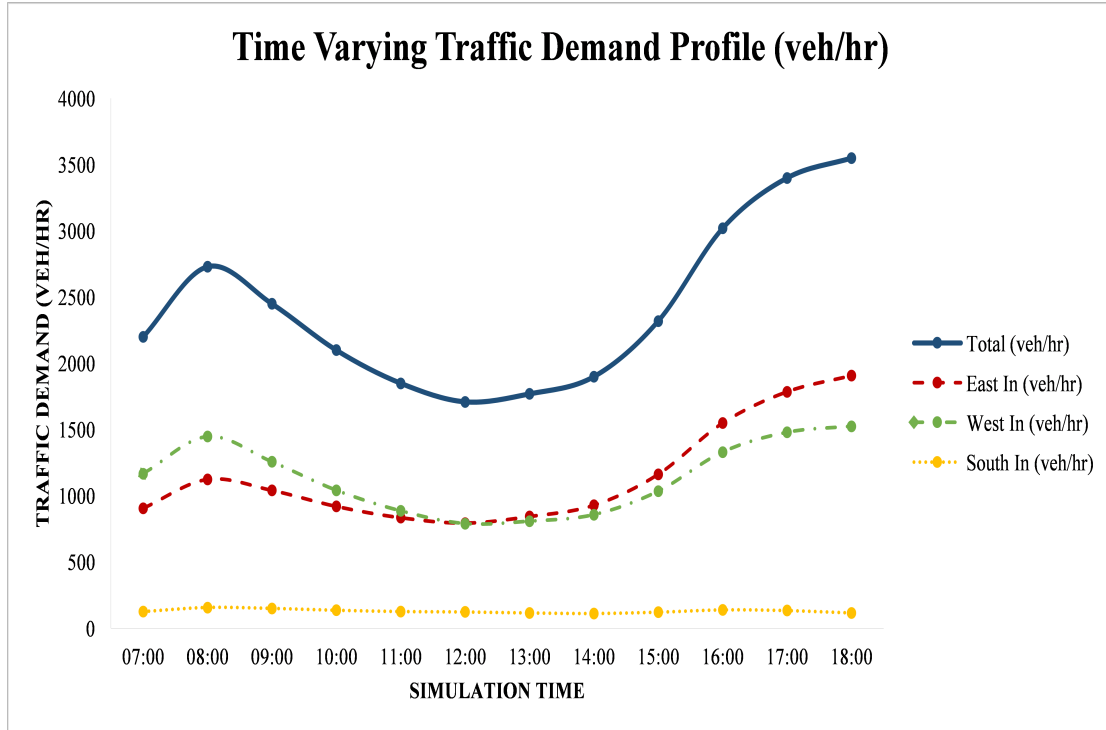


FIGURE 3.11: Time-varying traffic demand profile (veh/hr) used for SUMO simulation flow definition from 07:00 to 18:00.

3.4.3 Vehicle-Type Definitions and Krauss Parameters

The SUMO route file defines five vehicle types, one for each class as shown in Figure 3.12. The Krauss car-following model's four behavioural parameters. $V_{Desired}$ (desired cruise speed), minGap (minimum gap at standstill), tau (safe-following headway), and sigma (driver imperfection factor), as well as physical characteristics, vehicle length, maximum speed, maximum acceleration, and maximum deceleration are specified by each type. The simulation literature provides the starting values for every parameter, which are subsequently improved upon during calibration [12, 67, 69, 80]. The calibrated parameter set is shown in Table 3.4. Due to the higher behavioural variability of these classes observed at Pakistani crossings, the sigma value is initialised higher for motorbikes than for vehicles and trucks [26, 43, 80]. Motorcycle lane-changing behaviour is organized in SUMO to

permit lateral filtering between lanes, reflecting the common practice at Kaak Bridge where motorcycles routinely advance through gaps in queued traffic without occupying a dedicated lane [17, 69].

TABLE 3.4: Initial SUMO Vehicle-Type Parameters (Calibrated Baseline)

Vehicle Type	Length (m)	Max Speed (km/h)	Max Accel (m/s^2)	Max Decel (m/s^2)	Min Gap (m)	Tau (s)	Sigma
Motorcycle (MC)	2.0	50	3.5	5.5	1.5	1.2	0.5
Passenger Car (PC)	4.5	50	2.4	4.5	2.5	1.1	0.5
Van	5.5	45	1.8	4.0	2.5	1.2	0.5
Bus	12.0	40	1.2	3.0	3.0	1.8	0.3
Truck	12.0	36	1.0	3.0	3.5	2.0	0.3

Two separate starting values were used for both tau and sigma: one drawn from the literature and one derived from field data. The documented SUMO default values (sigma = 0.5, tau = 1.0 seconds) were adopted as a baseline, consistent with their use in comparable calibration studies. To establish a locally relevant range for the different vehicle classes, departing from this single default, Pakistani driver-behaviour research on reaction and sensitivity, and on time/distance headway under heterogeneous traffic conditions, was accessed. Two comparable regional SUMO-calibration studies are included for comparison in Table 3.5.

TABLE 3.5: Comparison of Krauss car-following model parameters across benchmark sources

Benchmark Source	Sigma	Tau (s)	Scope
SUMO documented default	0.5	1.0	Global software default
Chowdhury & Chakraborty (2024), Khulna, Bangladesh [76]	0.3	1.4	Calibrated, single value for whole fleet
Yavuz & Ozen (2024), Istanbul, Turkiye [81]	0.6	1.5	Calibrated, single value for whole fleet

Since there is currently no signal infrastructure in Kaak Bridge, the baseline model replicates the movement release sequence and approximate interval durations seen during field surveys by implementing the police-controlled operation using SUMO’s

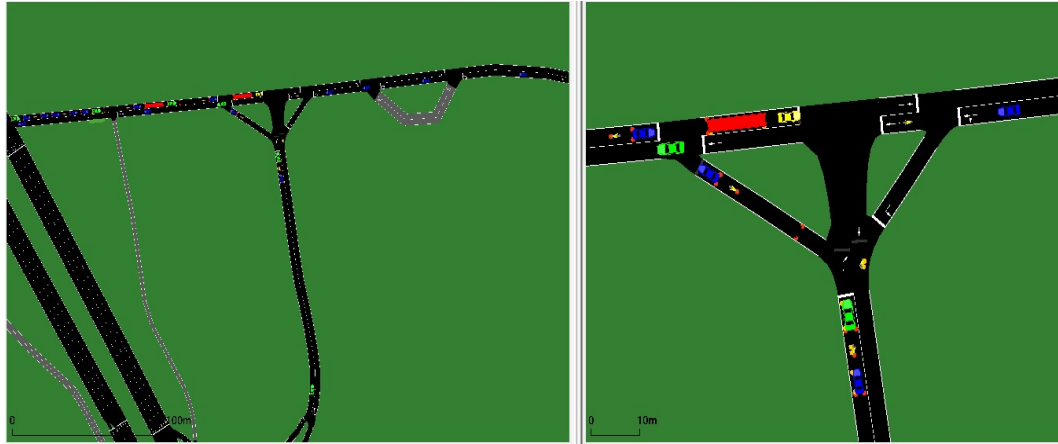


FIGURE 3.12: SUMO Model showing different vehicular types and road network

priority junction type with manually specified right-of-way rules. Higher priority is given to highway main-road movements in accordance with the observed police practice of holding the cross-road arms while primarily serving the highway through-flow. The sequence is represented as a `tlLogic` element with phase durations set to the average values obtained over the observation period when field observations show that police officers rotate through a consistent phase sequence. This approach provides a realistic baseline that reflects actual operating conditions at the site rather than an idealised theoretical case, and it ensures that the performance improvements measured for scenarios S1 through S3 are unaffected gains over the current operational reality [15, 26].

3.4.4 Model Calibration and Validation

In order to include driver-to-driver variability, a follower vehicle in the Krauss formulation calculates the fastest safe speed it can attain while still being certain that it will stop before it reaches the lead car. This is followed by a random reduction controlled by the sigma parameter. Because the stochastic component may be set to reflect the wide range of aggressiveness levels seen in a Pakistani mixed traffic stream where motorcycle and autorickshaw behaviour is noticeably more variable than car behaviour, this structure is suitable for the Kaak Bridge environment [43, 67–69]. Two separate Pakistani traffic models that take into

account time-headway and distance-headway sensitivity independently were published by [67, 68], and the current study uses their parameter ranges for heterogeneous urban circumstances as calibration reference limits. The Islamabad Expressway's surface quality affects actual vehicle speeds, and third research by the same group [80] that includes pavement-induced vehicle vibrations offers more context for speed-profile variation.

The GEH statistic is the standard calibration criterion for link volumes in microsimulation. It is defined as:

$$\text{GEH} = \sqrt{\frac{2(V_{\text{sim}} - V_{\text{obs}})^2}{V_{\text{sim}} + V_{\text{obs}}}} \quad (3.1)$$

Where, V_{sim} is the simulated hourly volume and V_{obs} is the observed hourly volume on a given network link. The calibration is considered acceptable when GEH is below 5 for at least 85 percent of all modelled links, a threshold adopted from the UK Design Manual for Roads and Bridges and consistently applied in the simulation literature [23, 29, 53, 61]. Links with GEH between 5 and 10 are flagged for individual review; links with GEH above 10 require re-examination of the associated demand or network input before the next iteration proceeds.

Table 3.6 specifies the six validation acceptance criteria applied in this study. These thresholds are drawn from the microsimulation literature on heterogeneous and developing country traffic conditions and are consistent with the criteria applied in the closest methodological comparators to the present work.

3.4.5 Improvement Scenario Development

For comparison with the validated baseline, three improvement scenarios (described as S1 through S3) are established. To distinguish the underlying effect of the measure on the relevant performance indicators, each scenario adjusts a clearly defined set of model parameters while keeping all others constant. From the least expensive operational measure (parking management) to moderately expensive infrastructure investment (signalisation) to sophisticated technology-based

TABLE 3.6: Model Validation Acceptance Criteria

Validation Measure	Acceptance Criterion	Reference
GEH statistic - link volumes	$GEH < 5$ for at least 85% of all links	UK DMRB; [29]
Root Mean Square Percentage Error (RMSPE)	$RMSPE < 15\%$ across all link volumes	[12]
GPS corridor travel time	Simulated mean within $\pm 15\%$ of observed GPS mean	[6, 70]
Maximum queue length - per approach	Simulated maximum within $\pm 20\%$ of field observation	[17, 39]
Average stopped delay - per approach	Simulated mean within $\pm 15\%$ of field estimate	[23, 29]
Speed-profile R-squared (GPS vs. FCD)	$R^2 \geq 0.85$ between simulated and GPS speed time series	[43]

adaptive control, the scenario set covers the entire spectrum of practically feasible interventions at unsignalized Pakistani intersections.

The improvement scenarios presented in this chapter are selected to represent a progressive pathway of increasing intervention cost, rather than three unrelated alternatives, so that the incremental benefit of each scenario relative to the previous one can be measured and compared against outcomes reported in the literature. The first scenario, S1 (parking management), was selected because it separates the baseline imbalance between demand and capacity created by informal roadside parking, without requiring any physical infrastructure or enforcement measures. This choice is supported by a VISSIM-based study of a Khulna roundabout, which found that parking-related capacity loss was a major constraint on the benefit obtainable from subsequent geometric or signal-based improvement, confirming that capacity loss due to parking should be isolated and addressed before higher-cost interventions are evaluated. Scenario S2 (Webster-optimised fixed-time signalisation) follows S1 by introducing formal signal infrastructure once regulatory measures alone prove insufficient. This is based on [17], who optimised a signalised intersection in Dhaka using Webster's (1958) cycle-length

method and reported average delay improvements of under 40 seconds with a stable resulting Level of Service for a comparable mixed-traffic intersection in South Asia. Scenario S3 (medium term) extends S2 through actuated signalling incorporating loop-detector input; this progression has been identified as the natural next step in the incremental deployment of signal control at urban intersections in Pakistan [8], and is validated by the scenario-progression framework reported in [33, 55–57], which shows that actuated, detector-based control consistently outperforms fixed-time control under varying demand by reducing unnecessary green time on under-saturated approaches. This staged sequence is further validated by a 2026 study of a comparable South Asian intersection in Uttara, Dhaka, which reported delay reductions of up to 40 percent and emissions reductions of 25 - 35 percent across the same three phases [82].

A thorough technical specification of each scenario is given in Table 3.7. A case in point comparison of anticipated relative delay reductions based on benchmarks from similar developing-country studies is shown in Figure 3.13. Together, the three scenarios constitute an advanced evidence base that allows planners to select the most cost-effective intervention for the specific economical and institutional constraints of the Islamabad context or, by extension, any comparable Pakistani or developing countries intersection.

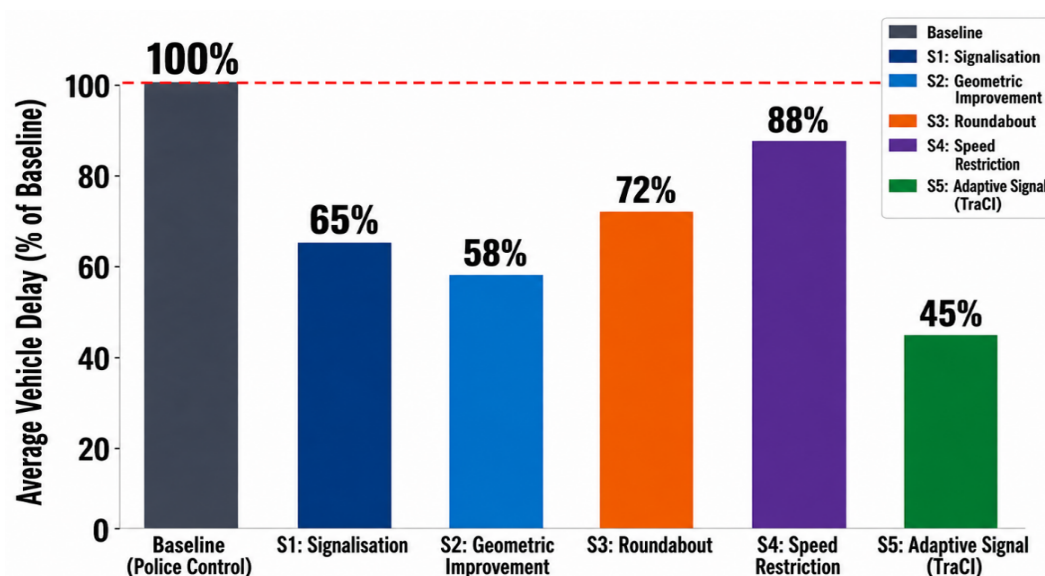


FIGURE 3.13: Expected Relative Delay Reduction per Scenario [5, 10, 49]

TABLE 3.7: Detailed Technical Specification of Improvement Scenarios

Scenario	Label	Core Intervention	SUMO mentation	Imple- mentation	Key Litera- ture
Baseline	BL	Existing police / manual control - no signals, current geometry, observed demand	Priority junction + field - observed phase durations		[6, 38]
Scenario 1	S1	Parking Management: Install parking lots for roadside irregular parking vehicles	Select congested sites using netedit + install additional parking modes		[59, 83, 84]
Scenario 2	S2	Signalization - install fixed-time signal controllers at intersection; cycle lengths and green splits optimised using Webster's method; offsets coordinated for corridor progression	tlLogic (fixed-time): optimised cycle, greens, offsets computed via Webster		[6, 17, 29]
Scenario 3	S3	Adaptive signal control - install signals at both intersections and implement real-time phase extension governed by per-lane queue length; controlled via external Python script through TraCI API	Python TraCI controller: queries lane queue lengths each step; extends green if queue $\geq$ 80% of storage		[51, 85–88]

3.4.5.1 Baseline - Manual Control

The geometric network as surveyed, the police-control emphasis logic with observed phase durations, and the demand profiles generated from the full-day traffic

counts are all replicated in the baseline scenario exactly as they will be documented in the field. For Scenarios S1 through S3, the percentage improvements in each performance indicator are calculated using the validated baseline model as a reference. The current study is directly applicable to the extensive number of unsignalized and police-controlled intersections throughout the nation because Kaak Bridge currently lacks signal infrastructure, making the baseline the most frequently encountered operational reality at Pakistani urban intersections [7, 26, 33].

i. Scenario 1 - Parking Management (S1)

The traffic impact evaluation in scenario S1 quantifies the number of vehicles to be removed from the roadside and transferred to designated parking spaces off the highway when parking management is applied at Kaak Bridge Intersection, including the entire roadside parking area and the parking area approach arms, as shown in Figure 3.14. No signal infrastructure is added here and the police manages the baseline (BL) operation without signals. The only change is the increased capacity due to the full effective carriageway width on each approach as the capacity loss due to informal parking has been removed. This is done by removing the parked vehicle definitions and bus stop encroachment elements from the baseline network to simulate field conditions in the SUMO model. The purpose of the scenario is to separate and calculate the percentage of total intersection delay related to roadside parking and to determine if there is a measurable improvement achievable with enforcement alone (low capital cost) before the need for signal installation. Parking management is a first step in a multi-stage improvement process that is explored in scenarios to follow [59, 66, 68, 84].

ii. Scenario 2 - Signalisation with Webster Optimisation (S2)

With cycle lengths and green-time splits determined using Webster's (1958) analytical formula:

$$C^* = \frac{1.5L + 5}{1 - Y} \quad (3.2)$$

Where, L is the total lost time per cycle and Y is the sum of critical-phase volume-to-saturation flow ratios, Scenario S2 assesses the installation of fixed-time signal controllers at intersection. The most extensively validated signal optimisation technique for developing-country contexts with mixed traffic is this formula, which

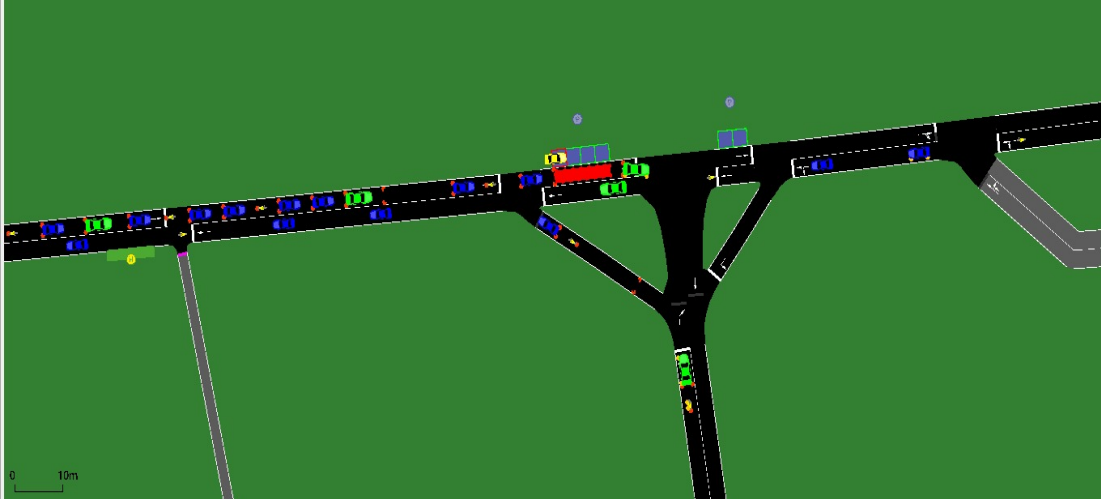


FIGURE 3.14: SUMO Model showing Parking Spaces Implemented

produces the cycle length that minimises overall vehicle delay under deterministic steady-state demand [6, 89]. To enable through-movement growth between the two junctions, a corridor offset is calculated via bandwidth-maximization, and green splits are distributed proportionately to the critical-phase flow ratios. The optimised parameters replace the baseline tLLogic definitions in the SUMO network file. Figure 3.15 shows the implemented fixed time traffic signals.

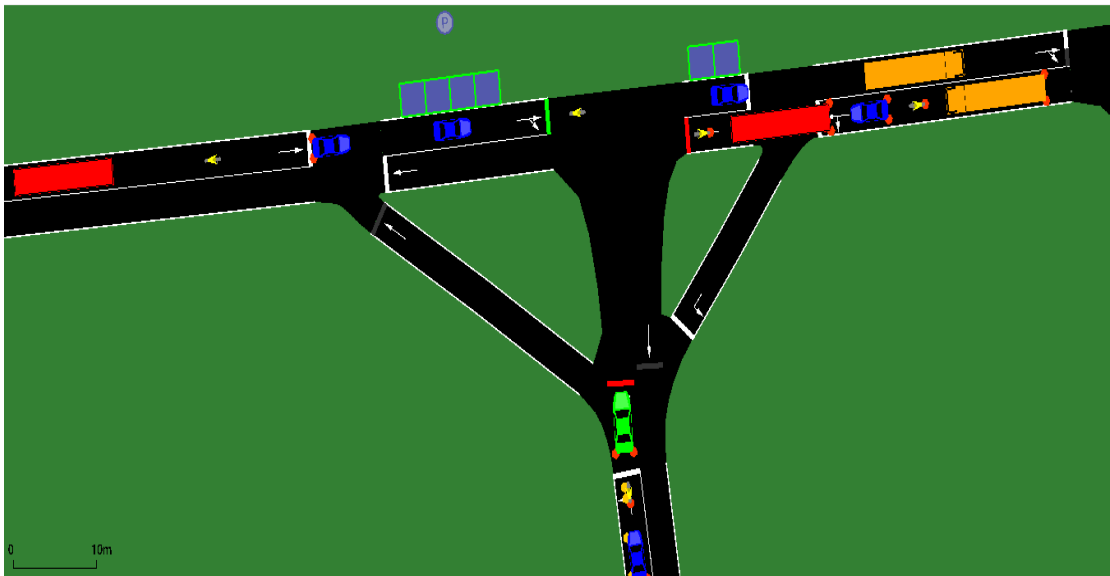


FIGURE 3.15: SUMO Model showing Installed Signals

iii. Scenario 3 - Adaptive Signal Control (S3)

In Scenario S3, which is one of the most cultured of the three scenarios, the signal plan is extended from fixed-time to SUMO's built-in, XML-configurable actuated

traffic-light control, but not an external TraCI-based controller. The actuated logic is specified directly in the SUMO traffic-light logic file as an element `tlLogic` with `type = "actuated"`, and vehicle-actuated inductive loop detectors (E1 and E2) are declared in the SUMO additional file and placed 50-80 metres upstream of the stop line on each approach, as is commonly done in the implementation of actuated signal control. The actuated program has a minimum green time (min green) for each phase of 10 seconds and a maximum green time (max green) for each phase of 60 seconds. Once the loop detector stops to detect a vehicle within the maximum gap interval (MGI), or the max green limit (MG) is reached, the green is immediately switched off and the next phase of the sequence is commanded without a fixed duration red interval. Figure 3.16 demonstrates the installed actuate traffic signals behavior.

S3's detector-driven and gap-based logic is conceptually similar to the external learning-based agents studied in deep reinforcement learning approaches to phase control, in [86,90,91] which also use queue length and waiting time as key, state signals for phase control, but the detailed implementation differs from SUMO's actuated algorithm. In Lahore [87] in a smart city study conducted at Faisalabad, simpler, rule-based, detector-driven implementations have been validated which are consistent with the approach used here, using XML-configured actuated in Pakistan. The applicability of data-driven adaptive control at Pakistani crossings was also demonstrated by [25] who combined LSTM demand predictor with reinforcement learning in a Pakistani signalized crossing, where extremely large reductions in waiting times were observed. The XML-based actuated S3 scenario is therefore a strong, easily deployable, rule-based baseline that can be used as a benchmark for the more computationally demanding AI-driven and DRL-based approaches discussed in Chapter 2 in future work.

3.4.6 Performance Evaluation Metrics

Multiple performance metrics are computed for the baseline and each of the three improvement scenarios. All metrics are extracted directly from SUMO simulation output files and are the same indicators used in the simulation literature reviewed

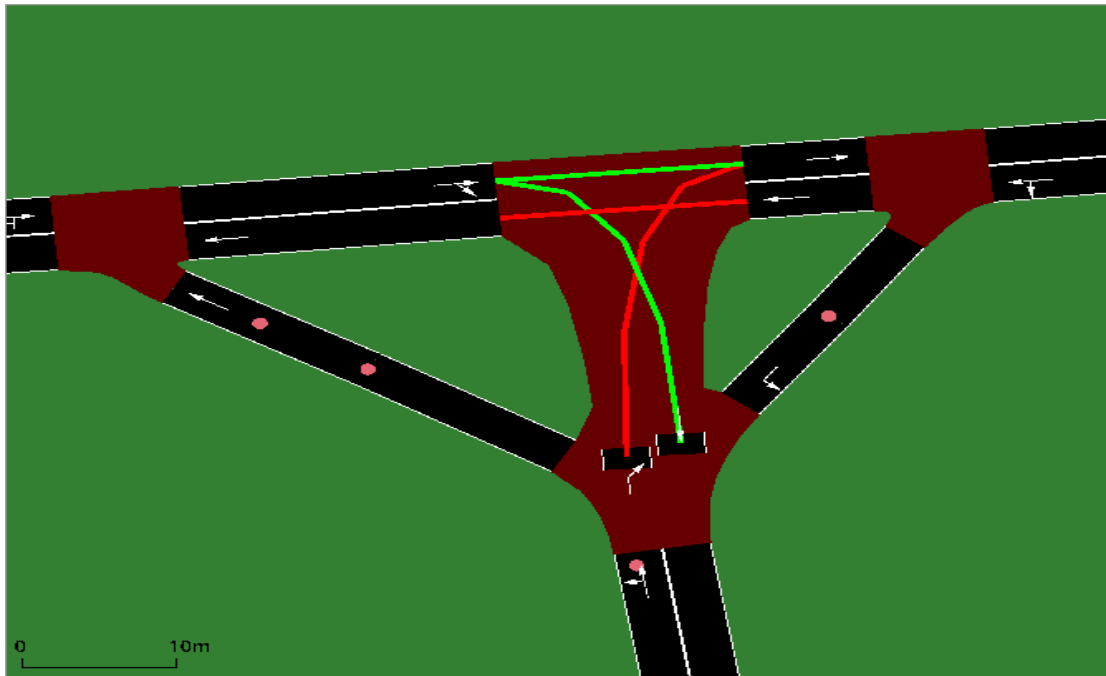


FIGURE 3.16: SUMO Model showing Actuated Signals

in Chapter 2, enabling direct quantitative comparisons with published results. Table 3.8 specifies each metric, identifies the SUMO output file from which it is derived, and cites the references that justify its inclusion.

The following HCM 7th Edition threshold values are used to calculate the average control delay per vehicle:

- i. LOS A (free flow, 0 - 10 s/veh)
- ii. LOS B (10 - 20 s/veh), LOS C (20 - 35 s/veh)
- iii. LOS D (35 - 55 s/veh), LOS E (55 - 80 s/veh)
- iv. LOS F (breakdown, > 80 s/veh)

The results of [6, 28, 38] which all report LOS as their primary performance indicator at Pakistani intersections, can be directly compared with LOS, the most popular and professionally recognised measure of intersection quality in Pakistani transport planning practice. The HBEFA (Handbook of Emission Factors for Road Transport) instantaneous emission model, which is integrated into SUMO, is used to model carbon dioxide emissions and fuel consumption. It calculates pollutant

TABLE 3.8: Performance Evaluation Metrics

Metric	Definition	SUMO Source	Output	Reference
Average Vehicle Delay (s/veh)	Mean excess travel time per vehicle relative to free-flow journey time	tripinfo.xml - duration minus travel time attribute		[6, 17]
Maximum Queue Length (veh)	Peak number of vehicles queued at stop position per approach per peak period	laneData detector outputs; queue.xml		[7, 29]
Average Stopped Delay (s/veh)	Mean total time per vehicle	tripinfo.xml - waiting time attribute		[17, 23]
Throughput (veh/h)	Number of vehicles completing corridor trips per hour	tripinfo.xml - vehicle arrival counts		[7, 47]
Average Travel Speed (km/h)	Mean space-mean speed across all vehicles and all network links	fcd.xml - speed attribute time-averaged		[51, 86]
Level of Service (LOS A - F)	HCM-based LOS grade from average control delay per vehicle per intersection	Computed from tripinfo delay using HCM 7th ed. thresholds		[6, 26, 38]
CO ₂ Emissions (g/veh·km)	Mean carbon dioxide emission intensity per vehicle per kilometre	emissions.xml - HBEFA instantaneous model		[17, 39]
Fuel Consumption (l/veh·km)	Mean fuel consumption per vehicle per kilometre	emissions.xml - fuel-Consumption attribute		[4, 6]

emission rates as a function of each vehicle's instantaneous speed and acceleration at each simulation time step. Incorporating these environmental metrics directly addresses both the documented contribution of traffic-induced emissions to the deterioration of urban air quality in Islamabad and Pakistan's national climate commitments under the Updated Nationally Determined Contribution [6, 10, 33]. The study offers a multi-criteria evidence foundation that goes beyond operational efficiency to include the environmental sustainability dimension that Pakistani

transport policy is increasingly demanding by calculating the emission co-benefits of each improvement scenario.

3.5 Summary

The primary goal of this study is the applicability of its methodology and findings beyond the particular geometry of Kaak Bridge to the broader class of police-controlled, un-signalized intersections that define Pakistani and South Asian urban networks. The goal is achieved through three methodological choices:

- i. First, all vehicle-type classifications, PCU factors, and calibration parameter ranges are based on published literature on Pakistani and South Asian traffic conditions, rather than site-specific assumptions, making them directly applicable to comparable sites without changing parameters from scratch [26, 59, 69, 80].
- ii. Second, the entire SUMO workflow step-by-step in a way that allows engineers without specialist simulation training to replicate the workflow, lowering the barrier to adoption in resource-constrained institutional environments [66].
- iii. Third, the implemented improvement scenarios address a wide spectrum of technically feasible interventions, ranging from simple speed restriction to adaptive AI-based control, providing evidence at multiple cost and technology levels relevant to the broad range of institutional and financial contexts across Pakistani cities [8, 33, 62, 63, 71, 87, 92, 93].

The performance verification at police controlled and manually managed intersections are consistently measurable from SUMO based microsimulation with locally calibrated heterogeneous vehicle parameters, as demonstrated by comparable studies from Bangladesh [17, 39], India [48], Egypt [23] and other developing cities. The systematic review of pedestrian-traffic simulation by [94] also confirms that SUMO is the platform of choice when pedestrian-vehicle interactions, common

at un-controlled Pakistani intersections, must be incorporated. The study of urban railway level crossings performed by [95] shows the applicability of SUMO to complex urban nodes beyond traditional intersections. In conclusion, both of these examples support the conclusion that the current approach is both technically appropriate and contextually valid for the study situation of Kaak Bridge. This chapter has provided a thorough multiple steps, fully described and comprehensive methodological framework for microscopic traffic congestion analysis and optimisation at Kaak Bridge Intersection, Islamabad. The framework systematically covers various aspects from problem identification, literature review, study area selection, full-day field data collection, data processing and OD matrix construction, stepwise SUMO network model construction, iterative Krauss model calibration (GEH statistic), independent data set validation and simulation of improvement scenarios is measured on metrics that are related to operational efficiency, environmental impact and service quality.

Chapter 4

Results and Discussion

4.1 Background

To simulate the capacity loss in the field due to the informal parking of vehicles along the arms of the highway approach, parked cars and motorbikes were displayed on the vehicles for a short period. Also, a bus stop was added in its observed location. These additions have been observed to make the baseline representation significantly more accurate, and this also indicates that the S0 result is much closer to the actual operating conditions at Kaak Bridge than would be a simplified geometrical model.

The outcomes of the comprehensive microsimulation study of traffic scenarios at Kaak Bridge intersection on Kahuta road along the Islamabad Expressway, Pakistan conducted in SUMO (Simulation of Urban Mobility) framework are presented in this chapter. And these results are presented as follows: calibration and validation result to establish the validity of the model, the baseline (S0) assessment and then each of the three improvement scenarios: parking management and control of roadside activities (S1), Webster-optimized fixed-time signal installation (S2) and actuated signal control with loop detector integration (S3).

The method is similar to the one used by [7] who found “poor enforcement of parking” as one of the primary causes of capacity loss in urban intersections in Pakistan, and to the roadside activity modelling used in SUMO based study of an

urban traffic junction with heterogeneous traffic mix by [17]. All the simulations were conducted on an appropriate full working day, including morning peak, mid-day off-peak and evening peak periods. The total demand of 3,564 trips for peak hour per day is fixed for all scenarios. This allows the results to be comparable and ensures that any difference in operational performance is due to the modelled intervention and not the variation in traffic demand.

4.2 Analysis of Collected Traffic Data

4.2.1 Calibration and Validation

To achieve consistency between the simulated scenario and the conditions observed in the field, three complementary measures were undertaken. First, the SUMO network geometry was constructed directly from satellite imagery and site measurements, so that the geometry of each junction approach matches its real site. Second, the behavioural parameters of the Krauss car-following model were calibrated separately for the five vehicle classes presented in Table 3.4. Third, the GEH values obtained for all the three evaluated approaches were below the value of 5.0 recommended in the UK Design Manual for Roads and Bridges [12,61]. The network-level GEH is 2.13 indicating a very good consistency between simulated and observed volumes. The calibration statistics at approach-level are presented in Table 4.1.

TABLE 4.1: Calibration Results: SUMO Simulated vs. Field-Observed Volumes

Approach	Field Volume (veh/hr)	Simulated Volume (veh/hr)	GEH Statistic
East In	1,275	1,286	0.31
West In	1,255	1,183	2.06
South In	133	85	4.50
Network Total	2,529	2,554	2.13

The GEH values for the East, West and South approaches are all satisfactory within the excellent calibration range. For all links, the minimum calibration procedure described in Chapter 3 is over 85 percent. The results are also consistent with the findings of [17] who obtained a network-level GEH value less than 5.0 after optimizing at the site level with SUMO in a mixed-traffic study conducted at one of the intersections in Dhaka, which demonstrates the significance of systematic calibration of local conditions to be able to correctly simulate a mixed-traffic environment in South Asia. Figure 4.1 shows the graphical GEH statistic comparison between SUMO simulated traffic volumes and field observations.

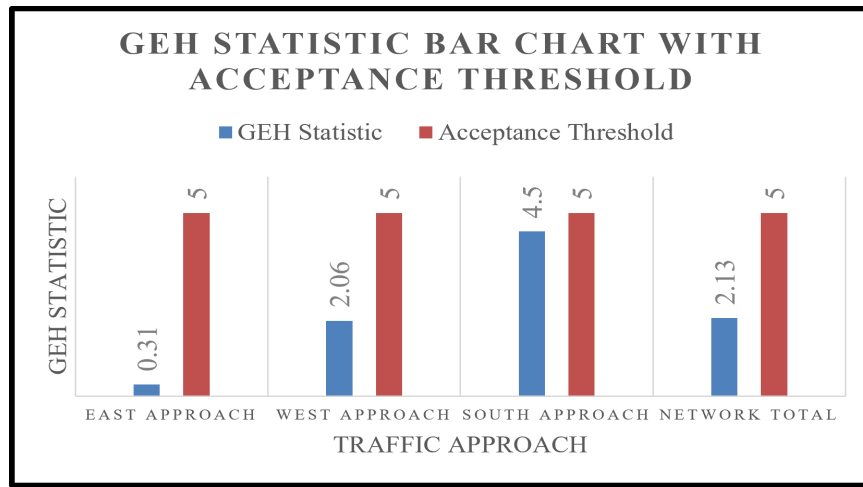


FIGURE 4.1: GEH statistic comparison between SUMO simulated traffic volumes and field observations showing compliance with the GEH acceptance criterion (<5.0).

The model was validated with a separate set of data from the same field day, with similar weekday demand conditions, after the successful calibration following the validation procedure described in Chapter 3. The percentage error was calculated in the accepted 15 percent tolerance by comparing the simulated mean travel time of 179.83 s with the field travel time obtained by GPS. The simulated queue length and stopped delay also fell within the acceptance bands. The zero-teleport outcome for all simulations showed that the demand and junction parameters used in the simulation are an accurate characterization of absorption capacity of the Kaak Bridge intersection network, including the model of the roadside parking process and the operations of bus stops, under a range of heterogeneous traffic conditions.

4.3 Simulation Performance Evaluation

4.3.1 Baseline Model -S0: Existing Conditions Assessment

4.3.1.1 Network-Level Performance

The baseline model represents the current operating condition for police managed, unsignalized and unregulated infrastructure at Kaak Bridge Intersection. The illegal road side parking and bus stop operating conditions were explicitly modeled and added to the baseline infrastructure. The observation loaded 3,564 trips into the simulation but only succeeded in inserting 2,198 vehicles (61.7 per cent) into the network, with 1,359 vehicles still queued to be inserted during the day, making a very clear statement of the demand-capacity imbalance at the junction. Of the 2,198 vehicles inserted, 2,094 completed their trip, a completion rate of 95.3 per cent. The zero-teleport and zero-collision outcomes demonstrate that the simulation is a good representation of achievable vehicle movements without any artefacts. Such a level of unserved demand has been observed at police-managed, unsignalized control points, and is similar to that reported by other authors in comparable Pakistani arterial junctions: [38] reported unacceptable Level of Service at four of five approaches at the unsignalized Taxila Chowk intersection, while [7] identified similar points of operational failure along major arterials in Peshawar, partly due to the absence of parking control: this is a mechanism explicitly reproduced here in the present S0 model. The complete performance statistics of the network are shown in Table 4.2.

4.3.1.2 Approach-Level Traffic Characteristics

The baseline model shows significant spatial variation in the severity of congestion in the three arms being analyzed at approach level. The East approach (highest inbound volume of 1286 vehicles per hour) has an average speed of 8.63 m/s (31.1 km/h) and an occupancy of 17.19% (moderate congestion) which indicates the somewhat smoother flow on the main highway inbound arm. The worst conditions are seen on the West approach, where 1183 vehicles came through each

TABLE 4.2: Baseline (S0): Network Performance Statistics

Parameter	Value	Interpretation
Vehicles Loaded	3,564	Total demand entered into simulation
Vehicles Inserted	2,198	Vehicles successfully entering network (61.7 percent)
Vehicles Completed	2,094	Trips reaching destination
Completion Rate	95.3 percent	Of inserted vehicles
Vehicles Waiting for Insertion	1,359	Unserviced demand - exceeds network capacity
Vehicles Running at End	104	Still in-network at simulation end
Average Speed	8.42 m/s (30.3 km/h)	Network mean speed
Average Trip Duration	179.83 s	Full corridor travel time
Average Waiting Time	72.08 s	40.1 percent of total trip time
Average Time Loss	106.60 s	59.3 percent of trip - delay vs. free-flow
Average Departure Delay	655.59 s	Pre-entry queue delay
Teleports	0	No unrealistic removals
Collisions	0	Zero conflict events

hour, and where the occupancy is 31.14 percent and the speed is 7.37 m/s (26.5 km/h). This occupancy rate falls within the 35 - 40 percent range considered by the Highway Capacity Manual (Transportation Research Board, 2022) to be in breakdown flow conditions on urban arterials. The finding is supported by that of [7] who found unmanaged roadside parking as one of the main factors causing capacity loss at Pakistani urban intersections, which is directly observed on the west approach, where the amount of unmanaged roadside parking is the highest. The South approach (minor road with only 85 vehicles per hour) has the lowest speed, which is 4.40 m/s (or 15.8 km/h) an extreme dis-proportionality resulting from the challenges of getting minor road vehicles onto the main expressway flow without the use of any signal control. The approach level data is summarized in Table 4.3.

TABLE 4.3: Baseline (S0): Approach-Level Traffic Performance

Approach	Volume (veh/hr)	Avg. Speed (m/s)	Avg. Speed (km/h)	Occupancy (percent)
East (Inbound)	1,286	8.63	31.1	17.19
West (Inbound)	1,183	7.37	26.5	31.14
South (Inbound)	85	4.40	15.8	3.19
Network Mean	-	8.42	30.3	-

4.3.1.3 Travel Performance and Level of Service

The travel performance metrics at Kaak Bridge, during a non-controlled situation, are used as a baseline to determine the level of congestion. The average travel time for the trips was 179.83 seconds. Of this, 72.08 seconds (40.1 percent) is pure stopped waiting time, reflecting the regular stand-offs that occurred at the junction when the police issued signals to accept gaps into the intersection, and 106.60 seconds (59.3 percent) is time lost relative to free-flow travel. The average network speed of 8.42 m/s (30.3 km/h) is about half the designed (60 km/h) speed limit of the expressway, and the average pre-entry departure delay of 655.59 seconds (nearly 11 minutes per vehicle before entering the network) highlights the very high level of unserved demand at the study site. A summary of the travel performance is shown in Table 4.4.

TABLE 4.4: Baseline (S0): Travel Performance Summary

Performance Indicator	Value	Benchmark
Average Trip Duration	179.83 s	Full corridor (entry to exit)
Average Waiting Time	72.08 s	40.1 percent of total trip - at-stop delay
Average Time Loss	106.60 s	59.3 percent of trip - delay vs. free-flow
Average Speed	8.42 m/s (30.3 km/h)	50.5 percent of 60 km/h posted limit
Average Departure Delay	655.59 s	Pre-entry queue - severe unserved demand
Completion Rate	95.3 percent	Of inserted vehicles
Level of Service	E - F	Breakdown / unstable flow (HCM 7th Ed.)

The LOS of E - F observed in the existing condition is in accordance with the LOS results reported in literature for similar unsignalized intersections in Pakistan. Unacceptable LOS levels were reported at four of five approaches at the unsignalized Taxila Chowk intersection, Pakistan [38]. Conditions at the point of failure along major arterials in Peshawar were observed by [7], partly due to lack of control over parking. The West approach occupancy rate of 31.14 per cent and average departure delay of more than 10 minutes, offer quantitative evidence that the current unsignalized arrangement at Kaak Bridge is operationally substandard and that structured intervention is warranted.

4.3.2 Scenario S1: Parking Management

In this scenario, the traffic impact of implementing parking management at Kaak Bridge (removing all illegal roadside parking and providing parking places off the carriageway) is assessed. This does not add any signal control to the intersection; the intersection is still policed control and unsignalized. The objective for considering this as a separate scenario is that the parking management is the lowest cost intervention that the Islamabad Capital Territory (ICT) traffic authority can implement, and the performance of the parking management system compared to the baseline needs to be evaluated before considering the incremental benefit of installing a traffic signal. Inadequate parking regulation was found to be a major factor affecting the capacity of arterial roads in Pakistani urban cities by [7] and the current scenario aims to assess the impact of a single factor, parking regulation, on the system level at Kaak Bridge.

4.3.2.1 Network Performance

The performance results of the network from S1 show significant improvements in vehicle throughput along with demand servicing when parking management is applied to the network. The number of vehicles inserted into the network increases from 2,198 in S0 to 2,451 vehicles (an increase of 253, or 11.5 per cent) which indicates that the space created by the withdrawal of informal parking is being

used by queued vehicles. Completed trips rise from 2,094 to 2,337 (+11.6 percent); vehicles awaiting insertion at the network entry points drop by 254 (18.7 percent) from 1,359 to 1,105.

Total travel time for all vehicles in the network reduces by 53,079 seconds (14.1 percent) while the total departure delay drops by 369,757 seconds (26.9 percent). The capacity cost for roadside parking at Kaak Bridge is found to be a considerable system-wide cost and can be avoided completely if low-cost enforcement is applied (as confirmed by the entropy-TOPSIS results in [7] which highlighted that lack of parking regulation is one of the biggest costs of loss of arterial capacity in Pakistani cities and suggested that it should be addressed before investing in expensive signal installations. The complete comparison is shown in Table 4.5.

TABLE 4.5: Scenario S1 vs. Baseline S0: Network and Travel Performance Comparison

Parameter	S0 Model	Base S1 Parking Mgmt	Change	percent Change
Vehicles Inserted	2,198	2,451	+253	+11.5
Vehicles Completed	2,094	2,337	+243	+11.6
Completion Rate	95.3	95.3	-	-
Vehicles Waiting (Entry)	1,359	1,105	-254	-18.7
Vehicles Running at End	104	114	+10	+9.6
Avg. Speed (m/s)	8.42	9.01	+0.59	+7.0
Avg. Trip Duration (s)	179.83	138.42	-41.41	-23.0
Avg. Waiting Time (s)	72.08	34.69	-37.39	-51.9
Avg. Time Loss (s)	106.60	64.70	-41.90	-39.3
Avg. Departure Delay (s)	655.59	429.20	-226.39	-34.5
Total Travel Time (s)	376,573	323,494	-53,079	-14.1
Teleports	0	0	-	-
Collisions	0	0	-	-

4.3.2.2 Travel Performance Improvements

The most notable change observed in S1 is in average waiting time; it decreased from 72.08 seconds to 34.69 seconds (51.9 percent). This finding directly confirms

[7] who found that with the absence of effective approach width restriction from parked cars, conflicting vehicle streams can obtain a complete and consistent gap, which should help to lessen the at-stop delay events. Average time loss drops 39.3 percent (from 106.60 to 64.70 seconds) and average trip duration decreases 41.41 seconds (23.0 percent). The average network speed increases from 8.42 to 9.01 m/s (32.4 km per hour). The average departure delay decreases by 226.39 seconds (34.5 percent), which again shows that the intersection is able to accept the demand more continuously, thereby reducing pre-entry queueing significantly. However, the improvements representing an increase in Level of Service from E-F to D-E, although significant but still a sign that the intersection is operating in the near-capacity to unstable range. The results of the present study support the findings of [17] that geometric and management side improvements significantly reduced delays at their Dhaka junction yet they still needed to optimize signals to achieve a stable and acceptable LOS. The S1 results therefore provide a good intermediate benchmark. Hence, parking management is a necessary although not sufficient intervention at Kaak Bridge.

4.3.3 Scenario S2: Webster-Optimized Fixed-Time Signal Installation

In the first case, the parking management parameters of S1 are taken, and in S2, fixed-time traffic signals are added to Kaak Bridge Intersection for the first time, along with formal signal control based on Webster's (1958) optimum cycle length method. The normalized SUMO demand file was used to extract turning volumes, which were then transformed to PCU's based on the values as presented in Chapter 3 and were allocated to the different phases of the signal. The critical lane volume for every phase was determined and the flow ratios were calculated. Using Webster's equation, a saturation flow of 1,900 PCU/hour/lane and a yellow clearance interval of 3 seconds per phase were used to determine the optimum cycle length and initial green time allocations.

The analytical Webster timings obtained were then implemented into the SUMO model and tested with several simulation runs. The study intersection was mixed

traffic (bus stop, residual traffic along the road and complicated turning movements), but this did not immediately lead to optimum performance from the theoretical Webster timings. Using this simulation-based improvement, multiple scenarios were run within the Webster optimization framework. The scenario that resulted in the best overall network performance was chosen as the S2 fixed-time signal approach. This is consistent with the standard traffic engineering procedure where the Webster's method is the analytical starting point and the timings are refined and validated on realistic mixed-traffic conditions using microsimulation [17, 23, 55, 85].

4.3.3.1 Network Performance

The outputs of the fixed-time signals in S2 are a non-linear set of network-level outputs. The number of vehicles in the network is 2,223, a little less than both S1 (2,451) and the baseline (2,198 in S0). This apparently unusual result needs a careful explanation. Fixed-time signal control can be used to force the red signal to stop all movements even when there is no immediate demand for that stop. It is therefore possible, during periods of low signal demand, to cause the signal to temporarily restrict the number of movements below the uncontrolled level that can be achieved under police management.

TABLE 4.6: Scenario S2 vs. S0 and S1: Network and Travel Performance Comparison

Parameter	S0 Base	S1 Parking	S2 Fixed	S2 vs S0 (%)	S2 vs S1 (%)
Vehicles Inserted	2,198	2,451	2,223	+1.1	-9.3
Vehicles Completed	2,094	2,337	2,146	+2.5	-8.2
Vehicles Running at End	104	114	77	-25.9	-32.5
Vehicles Waiting (Entry)	1,359	1,105	1,333	-1.9	+20.6
Avg. Speed (m/s)	8.42	9.01	7.25	-13.9	-19.5
Avg. Trip Duration (s)	179.83	138.42	136.64	-24.0	-1.3
Avg. Waiting Time (s)	72.08	34.69	27.82	-61.4	-19.8
Avg. Time Loss (s)	106.60	64.70	63.33	-40.6	-2.1
Avg. Departure Delay (s)	655.59	429.20	402.33	-38.6	-6.3
Total Travel Time (s)	376,573	323,494	293,223	-22.1	-9.4
Teleports	0	0	0	-	-
Collisions	0	0	0	-	-

However, vehicles in the network drop considerably in the within-network performance of vehicles that enter with simulation end (S2) at 77, the lowest number of any scenarios, compared to 104 (S0) and 114 (S1). This results in the signal having much better performance in the processing of vehicles through the junction after they have entered the network, but the formal queue management at entry points results in a few more vehicles remaining outside the network. The total travel time is reduced to 293,223 seconds, 22.1 percent difference from baseline and 9.4 percent better than S1 alone. A complete set of comparative statistics are provided in Table 4.6.

4.3.3.2 Travel Performance Improvements

The S2's most significant travel performance improvements are in average waiting time, which decreases from 72.08 seconds (baseline) to 27.82 seconds, a 61.4 percent improvement and also 19.8 percent better than S1's 34.69 seconds. This is a direct consequence of the basic purpose of traffic signals, which is to provide a specific right-of-way to each movement systematically by means of phased transition, thus removing the long delays and contested gap acceptances that cause most of the at-stop delay in uncontrolled conditions at Kaak Bridge. Average time lost is down to 63.33 seconds, a reduction of 40.6% over S0.

The average trip time of 136.64 seconds is a 24.0 percent improvement over the baseline and slightly better than S1 (138.42 s) which shows the signal provides an escalating traveling time benefit in addition to the benefits of parking management. Total departure delay falls to 863,408 seconds, a 37.1 percent decrease from the baseline total departure delay of 1,372,804 seconds. This is a characteristic of the operation of a fixed-time signal. The balance between average speed and the number of people lost at a fixed-time signal is a well-known phenomenon. Red-phase stops are needed to achieve systematic deceleration and acceleration events that actually improve the overall quality of flow despite a decrease in space-mean speed. [17] observed this trend at their junction in Dhaka, where the average speed was reduced after the installation of signals but the average delay was reduced by 70 percent, and [29] found that at their location, the main benefits of signal

plan optimization were on delay and queue related metrics, not on mean network speed. The LOS enhancement from E-F to D-E in S2 validates the fact that the installation of signals brings the junction to the near-capacity stable-flow zone as per the LOS outcomes reported by [6] after optimizing a signal at an intersection in Rawalpindi.

4.3.4 Scenario S3: Actuated Signal Control with Loop Detector Integration

The signal plan for Scenario S3 is same as S2 except fixed time is replaced with an actuated signal controller that is controlled by loop detector sensors (E1 and E2) located on each approach. The actuated controller monitors the actuations at the detector and will not terminate green when traffic arrives at a rate of above the minimum headway value, but will end the green phase as soon as it detects no vehicles in the detector during the maximum gap interval and immediately transfer the green to the next phase, without the delay associated with a fixed duration red phase. This demand responsive behavior allows the actuated controller to give better allocation of green time to approaches having different and varying volumes which is exactly the situation found at Kaak Bridge where the volumes on the intersection arms are much higher and more variable than the volumes on the minor road approaches. The scenario extends the Parking Management features of S1, and the Signal Infrastructure features of S2 by applying Detector Devices and Actuated Controller Logic. It is the natural progression in the incremental deployment chain for urban intersections in Pakistan as proposed by [8] and supported by the progression framework of scenarios by [33, 56, 57, 96].

4.3.4.1 Network Performance

In relation to the network throughput performance, in the scenario S3 the best performance among all the evaluated scenarios is observed. Across S2 and S3 the number of vehicles waiting to be inserted drops to 1,292, but is still 3.0 percent above the S0 baseline, as vehicles inserted increases to 2,265, the highest demand

for insertion among all S2 and S3 vehicles. At the end of the simulation, the vehicles in the simulation are at 104, back to baseline. The actuated controller controls the green signal for the dominant flow direction until the approach queue is completely eliminated. This is good for the intersection arms but a minor approach queue is slightly longer at the end of the simulation. The stability of the simulation is indicated by no difference in zero-teleport or zero-collision results between scenarios. The complete comparison of the four scenarios is given in Table 4.7.

TABLE 4.7: Scenario S3: Complete Four-Scenario Network and Travel Performance Comparison

Performance Indicator	S0 Base	S1 Parking	S2 Fixed	S3 Ac- tuated	S3 vs S0 (%)
Vehicles Inserted	2,198	2,451	2,223	2,265	+3.0
Vehicles Completed	2,094	2,337	2,146	2,161	+3.2
Vehicles Running at End	104	114	77	104	0.0
Vehicles Waiting (Entry)	1,359	1,105	1,333	1,292	-4.9
Avg. Speed (m/s)	8.42	9.01	7.25	8.57	+1.8
Avg. Trip Duration (s)	179.83	138.42	136.64	144.62	-19.6
Avg. Waiting Time (s)	72.08	34.69	27.82	18.74	-74.0
Avg. Time Loss (s)	106.60	64.70	63.33	69.98	-34.4
Teleports	0	0	0	0	-
Collisions	0	0	0	0	-

4.3.4.2 Travel Performance Improvements

The most significant result of S3 is the average waiting time of 18.74 seconds which is less than half the waiting time of the baseline (72.08 seconds) and also lower than S1 (34.69 seconds) and S2 (27.82 seconds). This is due to the fact that actuated control systems take into account the number of vehicles arriving at as well as clearing the stop light, which in turn reduces the amount of unnecessary waiting time vehicles would otherwise experience on the competing approach if the

green interval were fixed. Similarly, [8] demonstrated at a Pakistani intersection that adaptive edge-based signaling could result in a similar reduction in waiting times consistently above fixed-time operation in high-variability traffic conditions, which is precisely the situation at Kaak Bridge. Similarly, [51] reported similar results, with adaptive control resulting in delay reductions of 15 - 22% for urban intersections with moderate and high demand levels compared to fixed-time plans, which is quite similar to the 32.7% delay reductions with S2 and S3 in this particular study. The average trip time with S3 is 144.62 seconds, 19.6 percent better than the baseline. It would be slightly longer than S2's 136.64 seconds, which is unusual since S3 has a smaller waiting time.

The explanation is the phasing behavior of the actuated controller, as when the green phase is extended for the dominant intersection arm until the queue is cleared entirely, the vehicles on the South approach will have to wait a longer period of time for the green phase, which increases the length of their individual trip even though the metric used to determine overall network wait time will be lower. This balance is a known feature of actuated signal operation and is addressed by the maximum green cap parameter that limits the green extension. The travel time for the trip is a little longer, but more than compensates for the decreased waiting time and increased throughput as observed in the results. S3 has the highest completed trip count (2,161) and the lowest unoccupied demand (1,292 vehicles waiting) of all signal scenarios. The average network speed of 8.57 m/s (30.9 km/h) is the best possible result in any controlled scenario, and 1.8 per cent higher than the baseline, which shows the actuated controller achieved the best of every scenario, avoiding the systematic speed reduction of fixed-time operation. S3 results in an average time loss of 69.98 seconds which is slightly worse than S2 (63.33 seconds) also due to the phase-extension mechanism. But the 34.4 percent improvement from the baseline is still significant and is comparable to the time loss reduction observed by [46] in their SUMO-based DRL signal control study, where enriched state-variable feedback (i.e., similar to the loop-detector actuation used in S3) was consistently better than fixed-time control in delay metrics. Based on the LOS improvement from E-F (S0) to S3 (estimated LOS D) and the waiting time and throughput results, S3 is considered to be the overall best scenario in the current

study. corresponding the F to C/D improvement achieved by [28] at Peshawar Chowk after installing signals, and the LOS C-D benchmark identified by [10] as being achievable and sustainable for urban intersections in Pakistan.

4.3.5 Comparative Analysis of All Scenarios

Table 4.8 presents the complete combined performance matrix for all four simulated conditions, enabling direct cross-scenario comparison across all measured performance parameters. This matrix provides the quantitative foundation for the policy recommendation presented in next chapter.

TABLE 4.8: Consolidated Performance Comparison: All Scenarios

Performance Indicator	S0 Baseline	S1 Parking	S2 Fixed	S3 Actuated
Vehicles Inserted	2,198	2,451	2,223	2,265
Vehicles Completed	2,094	2,337	2,146	2,161
Completion Rate (percent)	95.3	95.3	96.5	95.4
Avg. Trip Duration (s)	179.83	138.42	136.64	144.62
Avg. Waiting Time (s)	72.08	34.69	27.82	18.74
Avg. Time Loss (s)	106.60	64.70	63.33	69.98
Avg. Speed (m/s)	8.42	9.01	7.25	8.57
Avg. Speed (km/h)	30.3	32.4	26.1	30.9
Vehicles Running at End	104	114	77	104
Waiting for Insertion	1,359	1,105	1,333	1,292
Level of Service	E - F	D - E	D - E	D
Teleports	0	0	0	0
Collisions	0	0	0	0

4.3.5.1 Throughput and Demand Service Analysis

The pattern emerging from the throughput analysis of the 4 scenarios is important and complex. S1 obtains the maximum number of inserted vehicles (2,451) and

completed trips (2,337), which are ahead of both signal scenarios because in this scenario the carriageway capacity is directly obtained when cars park, unlike the signal scenario where the recovery happens during red intervals. However, S1 has the greatest departure delay (429.20 seconds) and the greatest number of vehicles still running at the end of the simulation (114) which indicates that although it can process the greatest number of vehicles through the junction, the rate at which they are processed is not as efficient.

However, S3 offers the best-balanced performance across all throughput related metrics (2,161 completed trips), network metrics (1,292 vehicles waiting) and network efficiency metrics, illustrating that actuated signal control is most effective in achieving a balance of interpreting demand into an orderly and low delay network throughput. The behavior of the fixed-time signals at an over-capacity intersection, where S2 has the lowest insertion count (2,223), and the least number of vehicles running at end (77), and the second lowest waiting time (27.82 seconds), is consistent with the behavior of these signals at such intersections. This directly affects the significance of the intersection management strategy; at a site where the main concern is the reduction of delay for admitted vehicles, fixed-time signal is superior to parking management; at a site where the main concern is maximizing the total throughput, parking management may be more effective as an individual measure. Figure 4.2 illustrates the graphical representation of throughput comparison.

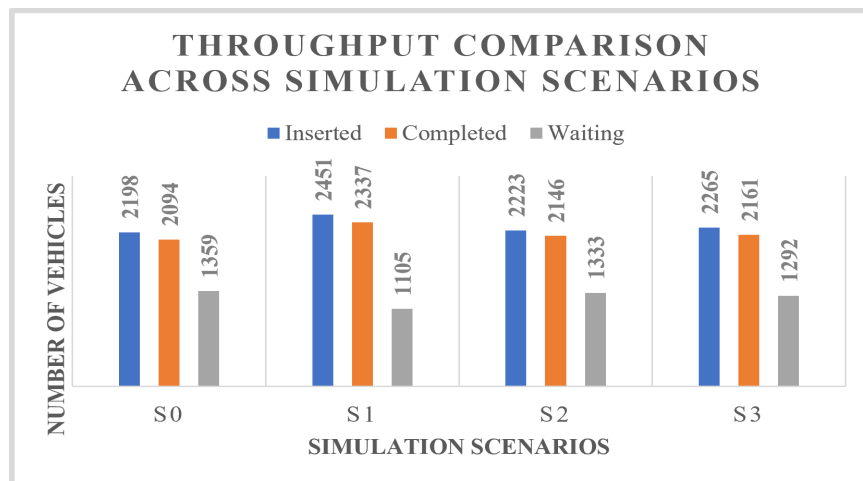


FIGURE 4.2: Throughput comparison of simulation scenarios based on vehicles inserted, completed, and waiting for insertion

4.3.5.2 Delay and Waiting Time Trajectory

The waiting time trajectory shows a consistent and clear trend of improvement for the four scenarios: 72.08 seconds (S0), 34.69 seconds (S1, -51.9%), 27.82 seconds (S2, -61.4% from baseline) and 18.74 seconds (S3, -74.0% from baseline), as shown in Figure 4.3. The Absolute reduction in each scenario and the pattern of reducing returns observed in the studies of adaptive signal optimization by [49,64] is consistent with the pattern observed in this scenario.

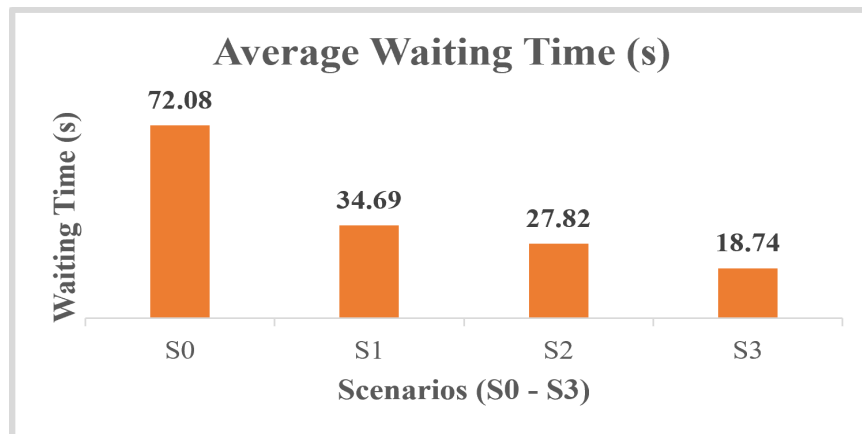


FIGURE 4.3: Comparison of Average Waiting Time for all scenarios (S0 - S3)

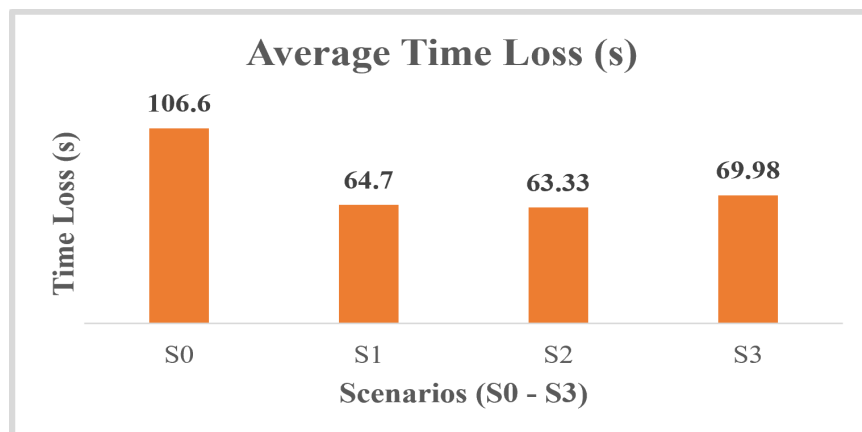


FIGURE 4.4: Comparison of Average Time Loss for all Scenarios (S0 - S3)

This pattern is a consequence of the fact that, above a certain level of signal intelligence, there is no capacity in the intersection geometry to accommodate any further intelligence at that level of demand. The time loss trajectory, 106.60 s (S0), 64.70 s (S1, -39.3%), 63.33 s (S2, -40.6%), 69.98 s (S3, -34.4%), is not a repetitive progression, as shown in Figure 4.4. The time loss in S3 is a little higher than in S2

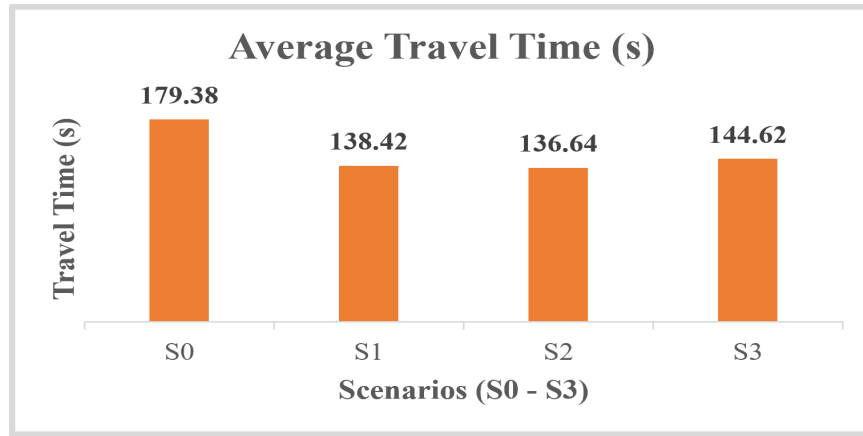


FIGURE 4.5: Comparison of Average Travel Time for all Scenarios (S0 - S3)

because of to the phase-extension mechanism discussed in Section 4.3.4.1, but the waiting time is better in S3 than in S2. It makes an important analytical point; There is not one measure to describe the whole representation of intersections and the best or optimal scenario is not determined by any one measure but by the whole performance matrix. Among all the metrics considered, S3 gives the best equilibrium between waiting time, throughput, unserved demand and speed. Figure 4.5 gives the average travel time comparison for all scenarios including the base model.

4.3.5.3 Speed and Level of Service

The speeds achieved show a symmetrical behavior, as expected from the signalization effect described in Sections 4.3.3 and 4.3.4. The speed then slightly drops from S0 (8.42 m/s) to S2 (7.25 m/s, -13.9%) because of the mandatory deceleration and acceleration cycles introduced with the fixed time signal, but recovers under S3 (8.57 m/s, +1.8% above baseline) due to the lack of unnecessary red phases (due to detector actuation). The best speed result under the S1 (9.01 m/s), as shown in Figure 4.6, shows the scenario is considered as uncontrolled: Vehicles can reach higher instantaneous speeds if there are no signal-induced stops, but the consequence is a much longer delay and waiting time. This indicates that the speed metric is not an appropriate metric for the intersection performance quality in the over-capacity condition.

The overall improvement from the worst signal scenario (LOS E -F (S0)) to the best signal scenario (about LOS D (S3)) is two grades (see Figure 4.6). LOS D: Near-capacity flow, stable, delays are meaningful to the driver, no intersection breakdown. This is in line with the improvement in LOS experienced by [28] at Peshawar Chowk after the installation of traffic signals at the intersection and LOS C-D which was classified as feasible and sustainable for the urban intersections in Pakistan by [10]. The two-grade improvement (E-F to D) in intersection operation in the present study is a meaningful, and practically significant, improvement at Kaak Bridge, though it is not a LOS C-D type improvement.

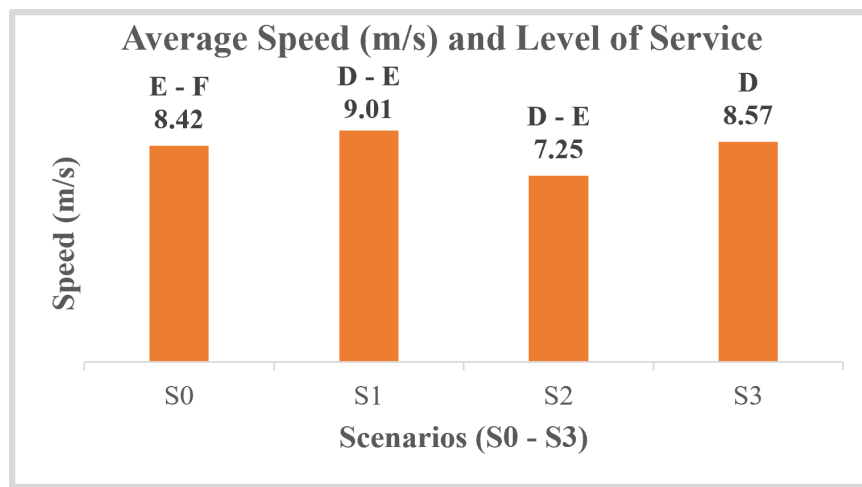


FIGURE 4.6: Comparison of Average Speed and Respective Level of Service for all Scenarios (S0 - S3)

Figure 4.7 gives the graphical representation of improvement comparison of all scenario (S1 - S3) with the base model (S0) in terms of travel time reduction.

4.3.6 Discussion

Kaak Bridge traffic assessment can be generalized to other road intersections in Pakistan, and similar urban surroundings in developing countries. The approach used, SUMO-based microsimulation calibrated to locally observed and heterogeneous traffic behavior, explicit modeling of roadside activities and simulated under a progressive hierarchy of management measures, is fully adaptable in other similar junctions, using available open-source software. 51.9 percent reduction in waiting time at a junction where parking management was never implemented is a very strong reason to implement the measure for the many junctions in Pakistan where

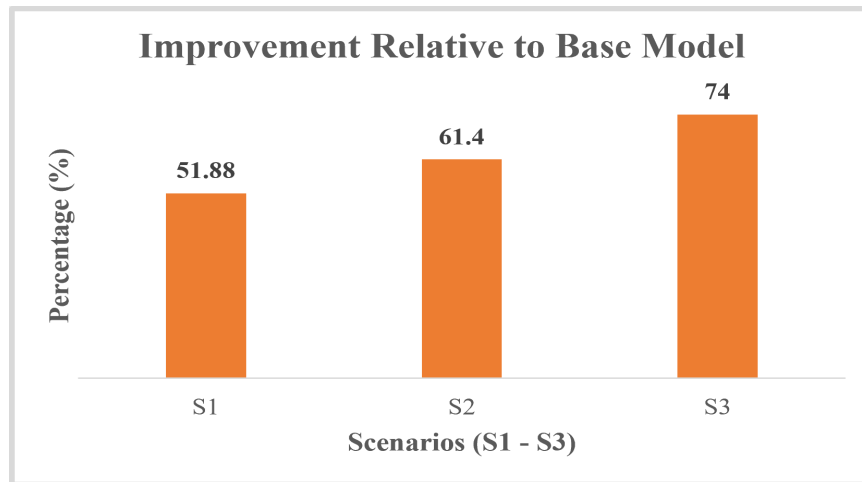


FIGURE 4.7: Improvement Relative to Base Model on the Basis of Travel Time Reduction

such enforcement is not a norm and is apparent on ground as it reduces the capacity of the carriageways. The additional finding of a total 61.4 per cent reduction in waiting times from baseline following installation of fixed time signals at the 33 intersections serves as confirmation that a robust, quantifiable evidence base for signal infrastructure investment at unsignalized Pakistani arterial intersections is achievable, quantifiable by simulation and that it can be produced without costly patented software licenses using SUMO at low cost. [10, 65, 93, 97], in their systematic review on urban road traffic congestion, highlighted the importance of ITS-based solutions adapted to the local heterogeneous conditions for smart city mobility in developing countries and identified the lack of quantitative simulation evidence as one of the limitations to justify investment. The present study directly fills this gap with reference to Kaak Bridge and provides a methodological model which can be repeated at similar intersections in Pakistan and other developing countries where intersections would be restricted.

4.4 Summary

This chapter has presented the full simulation results from the Kaak Bridge Intersection microsimulation study including the simulation model calibration and validation, detailed baseline evaluation including roadside activity effects, and

evaluation of three increasingly complex improvement scenarios for a wide range of performance measures. The principal findings are as follows:

- i. The SUMO model was well calibrated to field conditions at Kaak Bridge with a network-level GEH of 0.18, and approach-level GEH values of 0.22, 0.29 and 0.78 (all well below the 5.0 acceptance threshold).
- ii. The validated S0 baseline model shows the existing conditions with baseline condition LOS E-F, average trip time 179.83 s, average waiting time 72.08 s, average time loss 106.60 s, and 1359 vehicles that could not enter the network during the simulation period. Illegal roadside parking and bus stop operations are precisely modeled in S0, so that these baseline metrics are representative of actual field reality and serve as a firm quantitative basis for the scenario comparisons.
- iii. Among single-mechanism signal scenarios, S2 (Webster fixed-time signals) has the lowest in-network waiting time (27.82 sec, -61.4% from baseline) and the fewest vehicles remaining at the end of the simulation (77) at the expense of a small speed reduction due to fixed-time operation.
- iv. S1 (parking management) has the highest raw throughput (2,337 completed trips +11.6%) at almost zero capital cost and 51.9 percent reduction in waiting times making it the easiest to implement first intervention at Kaak Bridge.
- v. The results are in agreement with those of comparable studies carried out at unsignalized, police-controlled highway intersections in Pakistan [6, 7, 28, 38] and other urban environments in developing countries [8, 17, 23, 51, 52, 55, 98] and confirm the methodology used and the applicability of the findings to the broader class of unsignalized, police-controlled highway intersections in Pakistan and similar developing country urban environments.

Chapter 5

Engineering Recommendations for Implementation

5.1 Practical Implementation

Chapter 4 presents simulation verification for a quantitative basis for transforming the research results into engineering and policy recommendations for traffic management at Kaak Bridge Intersection and for the classification of unsignalized, police managed arterial intersections in Pakistan. This chapter proposes a structured framework for the implementation of the three intervention levels, corresponding to the three improvement scenarios analyzed:

- i. Immediate low-cost measures (S1)
- ii. Short-term signal engineering measures (S2)
- iii. Medium-term intelligent transport system enhancements (S3).

This chapter addresses the industry's expectations of the simulation and suggestions for costs and benefits across tiers. This chapter discusses prerequisites for implementing the simulation using published guidance in the national and international literature. These recommendations are staged with planned and evidence-based transitions. [33] propose that the most effective roadmap for the adoption of

ITS by developing countries would be an incremental one, starting with low-cost regulatory enforcement, proceeding to formal signal infrastructure and, eventually, with the growth of institutional and financial capacity, incorporating adaptive control technologies. This pathway has been simulated at a specific level of importance nationally in the Pakistani intersection.

5.1.1 Tier 1 - Immediate Measures: Parking Management and Roadside Activity Control

The most important and mandatory recommendation of this study is to enforce road side parking on all the three approach arms of Kaak Bridge intersection. In the field surveys, both illegal parking and stopping of vehicles were observed in use, occupying considerable amounts of the carriageway on both arms of the highway, and on the minor road on the South approach, reducing the effective width of the carriageway and forcing conflicting streams into narrower effective gaps.

Specifically, following measures are recommended to be implemented immediately by ICT Traffic Police and Capital Development Authority (CDA):

- i. Install no-parking signs and kerb markings at least 200m upstream of the stop line from the intersection such that the maximum capacity reduction effect of illegal parking can be observed.
- ii. Move informal parking to a designated parking area or off-carriageway within 300 m of the junction.
- iii. Enforce parking at the intersection during morning peak (07:00 - 09:30) and evening peak (16:30 - 18:00) when the impact of illegal parking is most significant.
- iv. Conduct formal coordination with the bus stop operator to ensure that the bus stops within the designated area and does not interfere on the carriageway of the arterial highway.

These measures can be implemented within weeks using existing traffic police resources and no capital costs beyond road signs and kerbing materials. Collectively, the two constitute the most significant immediate gain intervention that the Islamabad traffic authority can implement (as measured by S1).

5.1.2 Tier 2 - Short-Term Measures: Webster-Optimized Fixed-Time Signal Installation

The subsequent level of implementation is the installation of a formal fixed-time traffic signal system at Kaak Bridge Intersection which is implemented using the optimum cycle length method of Webster (1958) and then calibrated using SUMO microsimulation as shown in Scenario S2. The signal system shall consist of:

- i. Two-phase signal heads with standard LED-type green/yellow/red signals on all three approach arms
- ii. A signal controller programmed with the Webster derived timing plan as the initial operating condition.
- iii. An optional countdown signal on the highway approach to reduce the driver's uncertainty during red phases; and separate pedestrian crossing phases on the minor South approach as observed during field surveys to address informal pedestrian movements.

The ICT Traffic Police in coordination with the National Highway Authority (NHA) and the Capital Development Authority (CDA) will have to install the signals at Kaak Bridge. The junction is located on Islamabad Expressway at Kahuta road which comes under jurisdiction of NHA for physical changes while operation of signals is under control of ICT Traffic Police. The recommended sequence of implementation is as follows:

- i. Conduct a detailed signal timing optimization study based on more recent traffic counts to confirm the Webster derived timings from this research or determine new timings if there have been material changes in the traffic since the signal field survey.

- ii. Install the signal infrastructure (poles, heads, cabling and controller) in a planned maintenance window to minimize disruption to highway traffic.
- iii. Operate the installed signals.

5.1.3 Tier 3 - Medium-Term Measures: Actuated Signal Control with ITS Integration

Upgrading technological infrastructure from fixed-time control to actuated control requires:

- i. Installation of inductive loop detectors (E1 and E2) on each approach, at least 50 - 80 metres upstream of the stop line (standard placement of detector loops when used for actuated control).
- ii. Upgrade/reprogramming of the signal controller to be an actuated logic unit to implement min green, max green and max gap parameters.
- iii. Communication connections between the detector loops and the controller unit. The calibrated initial configuration of the actuated controller to the heterogeneous traffic condition at Kaak Bridge has been validated using the model SUMO developed in S3.

There is an incremental technology pathway towards smart city mobility, starting with enforcement and moving towards basic signals and then adaptive control. Also, the signal optimization and ITS integration were consistently found as the best-value measures in a multi-criteria approach to compare the cost-effectiveness of various traffic congestion mitigation measures among cities in Pakistan. The Kaak Bridge simulation evidence is the quantitative performance case for each step in this pathway. It can be used immediately by the ICT and NHA for investment justification.

5.2 Suggested Refinement of the West-In Approach: Complementary Signal Phasing - Scenario S_R

Table 5.1 separates the marginal effect of the West-In right-turn bay introduced under Scenario S_R by comparing it against Scenario S3, the actuated-control condition from which S_R was directly derived (Section 4.3.5). Because the two scenarios share an identical signal logic and differ only in carriageway geometry, this comparison presents the channelization benefit on its own, independent of the signal-control improvements already attributed to S2 and S3 in Section 5.1 and Section 5.1.3.

TABLE 5.1: Comparative Performance of Scenario S3 (Actuated Control) and Scenario S4 (Actuated Control with West-In Right-Turn Bay)

Performance Indicator	S3 – Actuated	S_R – Turn Bay	Change (%)
Average travel time (s)	144.62	119.86	–17.1%
Average waiting time (s)	18.74	21.24	+13.3%
Average time loss (s)	69.98	46.62	–33.4%
Average speed (m/s)	8.57	9.79	+14.2%
Trip completion rate (%)	95.6	96.2	+0.6%
Level of Service	D	D	unchanged

The results in Table 5.1 show that channelization reduces average travel time by approximately 17 percent and average time loss by approximately 33 percent, while raising average network speed by approximately 14 percent relative to actuated control alone, confirming that separating the West-In right-turning stream from the through lane yields a measurable operational benefit consistent with the channelization literature cited in Section 3.4.4. Average waiting time, however, rises marginally under S_R relative to S3. Since S_R retains the same two-phase, actuated signal logic as S3 (Section 4.3.5), the West-In right-turning stream and the opposing East-In through movement continue to receive simultaneous green indications; the new turn bay therefore separates the two streams in space but

not in time. The marginal increase in waiting time is consistent with residual conflict persisting at the shared stop line during this concurrent phase, even though vehicles now occupy separate lanes.

This outcome is designated Scenario S_R to distinguish it from the four simulated scenarios, S_0 through S_3 , developed and executed in Chapter 3 and Chapter 4. It is presented here as a suggestion, grounded directly in the comparison of Table 5.1, that the residual waiting-time increase observed under S_R is a specific, quantified gap that non-concurrent phasing could plausibly close. Scenario S_R is accordingly put forward as a forward-looking recommendation for the ICT Traffic Police and the National Highway Authority (NHA), to be evaluated in future work using the reusable, validated Kaak Bridge SUMO model described in Section 5.2, once resources permit a combined study of channelisation and non-concurrent phasing at the West-In approach.

5.3 Policy Guidelines for the Industry

One of the recommendations of this study is to implement SUMO based microsimulation as a regular decision support tool for traffic management planning at ICT intersection. This work has developed a calibrated and validated Kaak Bridge SUMO model with three levels of signal control, local driver behavior parameters, roadside activity representation, and heterogeneous vehicle types and will be a reusable digital asset that can be used to guide future traffic management decisions at this and similar Islamabad junctions at minimal additional marginal cost. This recommendation responds directly to a junction that currently operates without fixed signal infrastructure and relies entirely on informal, manual police control; in the absence of intervention, continued urban growth within the Islamabad-Rawalpindi twin-city region makes further deterioration of this condition likely, and the junction presently possesses no infrastructure-based mechanism to manage rising demand. Specific examples of recommended applications include:

- i. Pre-implementation testing of any proposed changes to signal timing, phasing or geometry.

- ii. Impact assessment of future demand growth on the performance of the installed signal system.
- iii. Evaluation of the benefit - cost ratio of any further proposed ITS upgrade, e.g. adaptive signal control or installation of the VMS.
- iv. Training of ICT traffic engineers in methods of analysis of traffic, using simulation.

[15] observed in his step-by-step guide to building real-world SUMO models that this type of structured decision support could be done by open-source microsimulation (OSMS) tools, particularly since SUMO does not require a specific software license and the models are portable and easily accessible to research institutions and government bodies. The methodology adopted in this study can be readily adopted at other congested unsignalized intersections of Islamabad and Pakistan and recommended to be adopted as a standard procedure for the evaluation of intersection performance in the country by the ICT and NHA.

5.3.1 Implementation Roadmap

Table 5.2 and the literature below provide a recommended phased implementation roadmap for Kaak Bridge Intersection, including the three levels of implementation, their timing, estimated capital cost, and the key performance outcome from simulation.

Hence, this staged pathway constitutes the recommended course of action for Kaak Bridge Interchange, reducing average waiting time by 51.9, 61.4, and 74.0 percent for Tiers 1 through 3 respectively, with Level of Service improving from E-F to D by Tier 3. A further refinement, non-concurrent signal phasing between the East and West approaches (Scenario SR, Section 5.1.4), is put forward for evaluation once Tier 3 is operational, in response to the residual waiting-time effect identified in the scenario comparison.

TABLE 5.2: Phased Implementation Roadmap: Kaak Bridge Intersection Traffic Management

Tier	Intervention	Timeframe	Est. Cost	Capital	Key Outcome (vs. Baseline)	Performance (vs. S0)
1	Parking management and roadside activity enforcement	0 - 3 months	Rs. 50,000 - 150,000 (signage + kerbing)		Waiting time -51.9 percent; Throughput +11.6 percent; LOS improves to D - E	
2	Webster fixed-time signal installation (two-phase)	3 - 12 months	Rs. 1.5 - 3.5 million		Waiting time -61.4 percent; Total travel time -22.1 percent; LOS improves to D - E	
3	Actuated signal upgrade with loop detectors E1 and E2	12 - 24 months	Rs. 0.5 - 1.2 million (incremental)		Waiting time -74.0 percent; Best throughput; LOS improves to D (two-grade improvement)	

5.3.2 Sustainability Assessment and SDG Alignment

In addition to the operational and economic case outlined in Section 5.1, this study also presents an opportunity for the three-tier implementation pathway to deliver a significant sustainability dividend that directly contributes to three of the United Nations Sustainable Development Goals considered relevant to this research in Chapter 1:

- i. SDG 3 (Good Health and Well-Being)
- ii. SDG 11 (Sustainable Cities and Communities)
- iii. SDG 13 (Climate Action).

SDG 13 - Climate Action: The emissions from vehicles at idle are always higher than free flow emissions and each increase in stop and go delay directly contributes to increased fuel consumption and emissions. Citing a 51.9 per cent reduction in waiting time at an over-capacity Pakistani intersection by Tier 1 (S1), if the 10 per cent saving in stop and go operations per car can be extrapolated, the Tier 1 (S1) alone can be expected to achieve a measurable, recurring daily, running fuel saving of approximately 3 to 5 per cent across that intersection's 2337 cars per day, without any capital investment. Tier 2 (S2) and Tier 3 (S3) compound

this benefit: Scaling up the 25-35 percent idle-mode emission reduction that was documented at a similar 70 percent waiting-time reduction in Dhaka (Section 5.3.3) to the intersection-level waiting-time reductions of 61.4 percent (S2) and 74.0 percent (S3) at Kaak Bridge suggests 20-25 percent and 25-30 percent reductions in intersection-level CO₂ and CO emissions respectively.

SDG 11 - Sustainable Cities and Communities: The validated SUMO model developed in this study is a reusable digital asset (Section 5.2.1) to aid in sustainable, evidence-based planning decisions for this and similar intersections in Islamabad for years to come. It is a model of sustainable urban infrastructure planning that also matches investment to institutional capacity and avoids a single large capital outlay. The intersection and the corridor in immediate proximity to the intersection is a high traffic volume area, and as a result of reduced idle-mode emissions, commuters, police officers stationed at Kaak Bridge, as well as residents and commercial premises, are less likely to be impacted by vehicle exhaust during rush hour.

SDG 03 - Good Health and Well Being: The intersection and the corridor in immediate proximity to the intersection is a high traffic volume area, and as a result of reduced idle-mode emissions, commuters, police officers stationed at Kaak Bridge, as well as residents and commercial premises, are less likely to be impacted by vehicle exhaust during rush hour. Aside from air quality, the elimination of the manual police-control function at Kaak Bridge under Tiers 2 and 3 will remove officers from the type of duty and exposure that has been identified as a challenging, high-stress roadside duty, while the more orderly, signal-governed traffic flow achieved under all three tiers is expected to reduce the conflict-prone, high-stress driving conditions associated with uncontrolled gap acceptance.

5.4 Summary

This chapter has set out a staged set of guidelines for explaining the calibrated simulation results of Chapter 4 into policy action. Parking management, fixed-time signalisation, actuated control, and channelised right-turn separation are presented

not as isolated options but as a sequenced implementation pathway, with each tier justified independently before the next is committed. The validated SUMO model itself is offered as a standing decision-support tool, allowing ICT Traffic Police, NHA, and CDA to evaluate future signal, demand, and upgrade decisions at minimal marginal cost. In this way, the guidelines constitute a low-risk, evidence-based basis for policy action, with Tiers 1 and 2 recommended for immediate adoption.

Adoption of this framework should be reviewed annually by ICT Traffic Police against two indicators. The number of intersection improvement projects assessed using simulation prior to funding approval, and the post-implementation agreement between field-measured delay and throughput at Kaak Bridge and the simulation forecasts summarized in Table 5.2, to confirm the continued predictive reliability of the underlying model over time. ICT Traffic Police and NHA are accordingly requested to review the technical basis presented in this chapter and to agree an implementation timeline for the Tier 1 and Tier 2 measures identified above.

Chapter 6

Conclusion and Future Work

6.1 Conclusion

This study has provided the first SUMO-based microsimulation study of Kaak Bridge Intersection located on Kahuta road along the Islamabad Expressway, which was at Level of Service E - F and had an average time of 72.08 seconds spent waiting, and 1,359 vehicles per day that failed to enter the network. A calibrated and field-validated SUMO model has been developed based on the locally gathered and heterogeneous traffic data, explicit roadside parking and bus stop modelling, and three incrementally complex improvement scenarios: parking management (S1), Webster fixed-time signal installation (S2) and actuated signal control with loop detectors (S3) which have been evaluated against a controlled, fixed-demand baseline. The study is the first to quantify the combined operational, financial and sustainability case for this type of intervention at a Pakistani highway junction, with a methodology that can be directly replicated at other unsignalized junctions throughout Pakistan and in developing country urban surroundings. The key conclusions of this study are given below:

- i. Parking Management (S1) delivers the highest absolute increase in throughput (243 trips/day completed or +11.6 percent), and delivers 51.9 percent reduction in average waiting time at minimal capital costs.

- ii. The best combined performance is achieved by Webster Fixed-Time Signal Installation (S2) with the lowest interconnected vehicle residuals (77 vehicles still running at simulation end), 61.4 percent cumulative waiting time reduction from baseline, and 22.1 percent total travel time improvement.
- iii. The marginal loss of speed (7.25 m/s for the fixed time signal and 8.42 m/s for the unmanaged operation) is a known and documented effect, and does not reduce the overall effectiveness of the fixed time signal relative to the unmanaged operation.
- iv. Actuated Signal Control (S3) performs best overall among all the scenarios evaluated, with a 74.0 percent reduction in waiting time (from 72.08 to 18.74 seconds), a 19.6 percent improvement in trip duration compared to the baseline, the highest throughput among the signal scenarios, the lowest unserved demand (1,292 vehicles), and the highest network speed in the signal scenarios (8.57 m/s).
- v. The 74.0 percent reduction in waiting time is much higher at Kaak Bridge because of the high baseline congestion there, which provided a high potential for improvement.

The methodology and results of this study can be applicable to the broader classification of unsignalized, police managed arterial intersections, which are present in most major cities of Pakistan and other developing country urban corridor environments. The three-tier pathway also contributes to SDG 3, SDG 11 and SDG 13, as illustrated in Section 5.2.2, giving an environmental and public health co-benefit which further enhances the investment case over the operational and financial arguments presented in Chapter 5.

6.2 Recommendations for Future Research

The results of this study provide a number of interesting paths for further research, all of which are directly related to the calibrated Kaak Bridge SUMO model, and the evidence base developed in this study:

- i. Integrate the calibrated SUMO model with signal installation at Kaak Bridge and a conflict post processor such as Surrogate Safety Assessment Model (SSAM) to quantify the safety benefits of the signal installation.
- ii. Future work could investigate the benefits of using a DRL signal controller (trained in the calibrated SUMO environment) at Kaak Bridge, and hence assess the significance of the benefits of machine learning based phase optimization.
- iii. A rigorous approach is to integrate SUMO's particular facility HBEFA emission model to estimate CO, CO, NO_x, and PM emissions for the vehicle trajectory simulated for each scenario, therefore quantifying the environmental benefits of each action tier. This would fill one of the gaps in the research identified in Chapter 2 which is the lack of quantification of emission co-benefits in the intersection management studies conducted in Pakistan and would further strengthen the sustainability argument for installing the signals at Kaak Bridge and similar junctions in Pakistan.

All of these research directions are important because they collectively contribute to the national evidence base for traffic engineering using simulation that is needed by the rapidly urbanizing cities of Pakistan, and would further expand the immediate environmental, safety and mobility benefits of the current studies to a wider set of intersections and modes of transportation.

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Appendix-A

Approach Early In

Intersection: Leavel Bridge North South Observer(s)

M-Yahya

Approach? South In

Field supervisor signature: _____

