Study of Traffic Simulation Model for Heterogeneous Traffic

by

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Declaration

I hereby declare that

i) the thesis comprises of my original work towards the degree of Master of Technology in Information and Communication Technology at Dhirubhai Ambani Institute of Information and Communication Technology and has not been submitted elsewhere for a degree,

ii) due acknowledgment has been made in the text to all the reference material used.

Mayank Singh

Certificate

This is to certify that the thesis work entitled "Traffic Modeling for Mixed Mode Traffic" has been carried out by Mayank Singh for the degree of Master of Technology in Information and Communication Technology at *Dhirubhai Ambani Institute of Information and Communication Technology* under my/our supervision.

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Contents

Abstract

Mixed-mode traffic, consisting of diverse vehicle types with varying characteristics, holds significant importance over homogeneous traffic scenarios. Unlike homogeneous traffic, which comprises vehicles with similar attributes, mixed-mode traffic reflects the reality of real-world road networks. By encompassing different vehicle classes such as cars, trucks, rickshaws, motorcycles, etc, mixed-mode traffic captures the complexities and challenges that arise from their diverse operating characteristics. Understanding and modeling heterogeneous traffic is crucial for designing effective transportation systems that cater to the specific needs and behaviors of each vehicle type. Overall, recognizing the importance of mixed-mode traffic leads to more comprehensive and realistic transportation planning and management approaches that address the unique challenges posed by diverse vehicle types on road networks.

In this thesis, we have studied the aggregate behavior of mixed-mode traffic and investigated the macroscopic parameters of mixed-mode traffic to understand how they are correlated with each other. Later on, we analyzed the macroscopic parameters such as traffic flow, traffic speed, and traffic density for mixed-mode traffic using traffic simulator called SUMO (Simulation of Urban Mobility). Our results showed that traffic simulator SUMO can be used to effectively model mixed-mode traffic. As, the car-following parameters of mixed-mode traffic have been manually tuned in our study for SUMO. So, it opens up possibilities for using machine learning models to predict the parameters for further improvements.

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CHAPTER 1

Introduction

Intelligent Transportation System (ITS) technologies compute information about current and future traffic conditions. ITS applies Information and Communication Technology (ICT) for data collection and processing, advanced information retrieval techniques, and advanced computation technologies for the operation and management of the transportation network. Within the broader field of ITS, Traffic Modeling has been a subject of research since the 1940s. It primarily aims to describe road traffic by employing mathematical equations that relate traffic variables such as flow, density, and speed. These models capture spatial and temporal variations, aiding in estimating current and future traffic states, predicting patterns, and detecting changes in traffic behavior.

Traffic Modeling provides scientific insights and tools for predicting traffic flow, optimizing signal timings, assessing road capacity, evaluating ITS technologies, aiding emergency planning, and promoting sustainable transportation strategies. These applications contribute to more efficient, safe, and sustainable transportation systems.

The thesis focuses on the modeling of mixed-mode traffic. This will allow us for a comprehensive analysis of the interactions and dynamics between various transportation modes, including cars, trucks, mopeds, pedestrians, and more. By capturing the heterogeneity and inter-dependencies among these modes, modeling mixed-mode traffic provides insights into travel patterns, congestion hot-spots, and mode choice behavior.

1.1 Motivation

Mixed-mode traffic refers to a situation where different types of vehicles, such as cars, trucks, motorcycles, and bicycles, coexist and interact on the same road network. The extensive amount of literature that exists in the area of traffic flow theory may not be directly helpful in developing countries like India. Due to the presence of various vehicle types, such as bicycles, auto-rickshaws, cars, and bullock-carts, mixed-mode traffic in this context encompasses vehicles with distinct operating characteristics. These characteristics encompass factors like size, speed, acceleration, and maneuverability, creating a diverse and varied traffic environment.

As a result, any research on the traffic situation in a developing nation will be more realistic if it can take into account both "vehicular heterogeneity" and "weak-lane discipline" scenarios. It is necessary to comprehend how vehicles interact with one another not only in the longitudinal direction of the lane but also in the lateral direction with the existing traffic facilities.

Therefore, it is necessary to take a microscopic look while modeling the mixed-mode traffic. In this situation, a traffic simulator can be instrumental in understanding heterogeneous traffic dynamics by allowing us to replicate real-world scenarios and study the interactions among different vehicle types. By simulating different traffic conditions, it provides insights into traffic flow, congestion patterns, and the impact of various factors, aiding in the development of effective strategies for managing and optimizing heterogeneous traffic.

1.2 Objective

The objective of the thesis is defined as follows:

- Study the aggregate behavior of mixed-mode traffic.
- Investigate the macroscopic parameters of mixed-mode traffic and study how they are correlated with each other.
- Analyze how the different types of vehicles interact with each other in a road network.
- Simulate the mixed-mode traffic on a traffic simulator and analyse the macroscopic parameters such as traffic flow, traffic speed, and traffic density.
- Tune the car-following model parameters to reduce the mismatch between the macroscopic parameters observed in the data set and in the simulation for mixed-mode traffic scenario.

1.3 Thesis Outline

The remainder of the thesis is organized in the following manner. Chapter 2 presents the state-of-the-art of heterogeneous vehicular traffic flow modeling. This includes the applicability of traffic flow models in (ITS); the need to shift from a homogeneous modeling approach to heterogeneous flow modeling; the frameworks of heterogeneous traffic flow modeling at different granularity. Chapter 3 defines the problem related to mixed-mode traffic along with the assumptions. Chapter 4 discusses the data sets used for the experiment. Chapter 5 describes the experimental setup of the research and analyzes its results. Chapter 6 concludes this thesis by outlining the key findings and recommending future research directions.

CHAPTER 2

Related Work

In real-world scenarios, traffic flows consist of a diverse array of vehicles and drivers. The term "heterogeneous" (also known as mixed and multi-class) traffic flow is employed to describe the different operating characteristics of these vehicles, such as their physical dimensions, maximum speeds, and acceleration and deceleration capabilities. Additionally, the behaviour of drivers also differs within this heterogeneous traffic flow. Consequently, when faced with identical traffic conditions, vehicles and drivers exhibit dissimilar behaviours due to these inherent differences.

To propose a traffic model that captures the dynamics of road traffic, an analogy is drawn with hydrodynamic theory [1]. The road traffic is analyzed by breaking it down into fundamental components, which are then modeled based on similarities to hydrodynamic systems. This approach assumes that the flow of vehicles can be considered to the movement of a fluid through a pipe.

To study mixed-mode traffic, it is best to take a macroscopic view. Because, this approach requires fewer variables than other models and leads to decision-making quicker. Moreover, it allows for a broad representation of the traffic network, providing an overall understanding of the entire system.

The macroscopic models are usually derived from hydrodynamic models, resulting in describing the traffic as a flow of vehicles. The main variables used for describing its behavior are traffic flow, road density and average speed of vehicles. Traffic flow expresses the number of vehicles passing a location in a unit time [1]. If the number of vehicles measured by a sensor in an interval $\triangle t$ is N(t), the flow of traffic is expressed as:

$$q(t) = \frac{N(t)}{\triangle t} \tag{2.1}$$

Road density expresses the number of vehicles that are on a section of the road [1]. By using a pair of inductive loops it can be measured on a section determined by the location of the loops. If the section of road on which the density is measured is given by $\triangle x$ and the number of vehicles that are on this section is given by N(t), road density is the ratio between:

$$\rho(x,t) = \frac{N(t)}{\triangle x} \tag{2.2}$$

where $N(t)$ is number of vehicles occupying part of the unit section during the specified time t and $\triangle x$ is the length of section in 'm' or 'Km'.

The average speed of vehicles expresses the average road speeds of vehicles that are on a section of the road [1]. In practice, the value of the average speed (V_{m}) is obtained by averaging the speeds of vehicles passing over a sensor for a fixed period of time (considering a number K of measurements):

$$V_{\mathrm{m}} = \sum_{i=1}^{K} \frac{V(t_{\mathrm{i}})}{K} \tag{2.3}$$

where V_{m} is average speed of vehicles and $V(t_{\mathrm{i}})$ is the speed of a vehicle at time t.

The fundamental traffic diagram gives a relationship between traffic flow and road density. It can be used to predict the behavior of a road section. The general diagram is shown in Figure 2.1 [1].

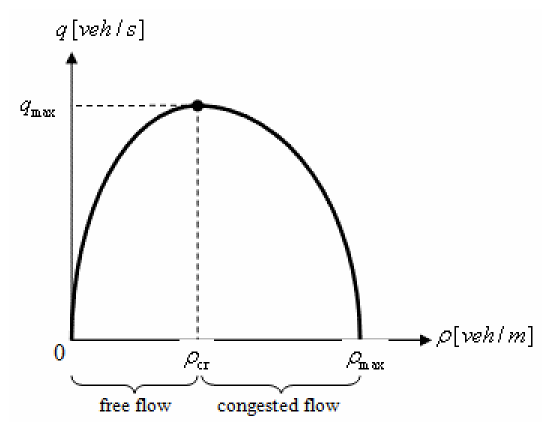


Figure 2.1: Fundamental traffic diagram

There are two distinct categories that correspond to different types of traffic:

- Free flow traffic: It is characterized by vehicles moving freely without restrictions at a speed equal to the recommended maximum limit for the road section, known as the free speed.

- Congested traffic: It is the traffic where vehicles travel at a speed below the free speed

In the free flow zone the density varies between zero and the critical density. Zero density implies to the case where there is no vehicle on the road. The critical density implies to the case where there are a number of vehicles on the road moving with a free speed, but after this value if the number of vehicles increases the speed begins to decrease and vehicles cannot travel anymore at free speed [1].

Congested area of flow is given by a density between the critical value and the maximum value. The maximum density implies to the case where the road is filled to maximum capacity and there are no moving vehicles [1].

In the context of macroscopic approaches, the focus shifts from the dynamics of individual vehicles to the dynamics of macroscopic quantities [5]. Specifically, the vehicle density $\rho(x,t)$ and average velocity $v(x,t)$ are considered as functions of space (x) and time (t). These quantities are obtained by averaging over a sufficiently large spatial region. Since the number of vehicles in a road segment can only change through vehicles entering or leaving the segment, a continuity equation holds for ρ and v

$$\frac{\partial\rho}{\partial t} + \frac{\partial}{\partial x}(\rho v) = 0 \tag{2.4}$$

where ρ is the density of the fluid, v is the velocity in the x-direction.

As one of the classic car-following models, Krauss model is a microscopic, space-continuous one, and it was established based on the safe speed [5]. The idea behind microscopic modeling of traffic flow is to capture the behavior of each individual vehicle based on the positions and velocities of nearby vehicles. Almost all car following theories are grounded on the premise that the movement of a vehicle *i* is primarily governed by the behavior of the preceding vehicle *i+1*.

In each time step the vehicle‘s speed is adapted to the speed of the leading vehicle in a way that yields to a collision-free system behaviour within the following simulation step(s).

The detail description is as follows: [5].

$$V_{\text{safe}}(t) = V_{\text{l}}(t) + \frac{g(t) - V_{\text{l}}(t)\tau}{\frac{V_{\text{l}}(t)+V_{\text{f}}(t)}{2b} + \tau} \tag{2.5}$$

where

- $V_{\text{safe}}(t)$: Maximum Safe velocity in time t
- $V_{\text{l}}(t)$: Speed of the leading vehicle in time t
- $V_{\text{f}}(t)$: Speed of the following vehicle in time t
- g(t): Gap to the leading vehicle in time t
- τ: Driver's reaction time (usually 1 second)
- b: Deceleration function

Typically, the speed of a following vehicle is lower than the safe speed and the maximum speed permitted on the road. This speed is often referred to as the "desired" speed and can be determined using the following equation.

$$V_{\text{des}}(t) = min[V_{\text{max}}, v(t) + a(V)\triangle t, V_{\text{safe}}(t)] \tag{2.6}$$

where V_{max} is the maximum speed allowed on the road in (m/s), a is the acceleration of the vehicle (m/s^2) and $\triangle t$ is the step duration of simulation.

2.1 Need for a Comprehensive Traffic Simulation Model in Indian Context

A realistic model of driving or driver behaviour must be a comprehensive model which models both lateral control (steering control) and longitudinal control (speed control) under the impact of both roadway and traffic features. According to this aspect of control, microscopic models can be categorised into (i) longitudinal control models, (ii) lateral control models, and (iii) comprehensive models and discussed in the present section [8].

2.1.1 Longitudinal Control Models

Longitudinal control models assume that the driver's behaviour is influenced only by leading vehicles travelling in the same path or lane. The process of achieving longitudinal control is referred to as car-following in transportation literature [8].

2.1.2 Lateral Control Models

Most of the work on lateral control models relates to how different roadway objects and obstacles initiate a lateral shift in the driver's path [8].

2.1.3 Comprehensive Models

The final goal of microscopic modelling is to be able to devise a comprehensive model which models both lateral and longitudinal control of vehicles as a comprehensive whole. Here, authors have developed CUTSiM as a comprehensive microscopic model, which is found to be more relevant in Indian perspective since it can be used for simulating the traffic stream with and without lane discipline [8].

2.2 Development of Simulation Model for Heterogeneous Traffic with No Lane Discipline

The development of the unidirectional traffic model is influenced by two recent models: Gunay's car-following model with lateral discomfort (2007) and Ravishankar and Mathew's vehicle-type dependent model (2011) [7]. While Gunay's model does not consider heterogeneity parameters, which are addressed in Ravishankar and Mathew's model, the latter does not account for non-lane-based car following or lateral interactions between vehicles. In an attempt to combine these two models, a set of rules is formulated for different scenarios, including free-flow conditions (Case-0), basic car following (Case-1), MES-based car following (Case-2), and veer-induced car following (Case-3). These rules determine the vehicle speeds based on the specific case that occurs under given time and conditions.

- The main objective of this research paper is to create a traffic simulation model that accurately replicates the unique characteristics of Indian road conditions, including heterogeneity among vehicles and the absence of strict lane discipline [7].
- Through observation, it has been noted that the following vehicle tends to make lateral adjustments in order to find better opportunities. Once a sufficient veering manoeuvre is completed, the following vehicle either starts following the leading vehicle or overtakes it based on the Effective Road Width (ERW) available [7].

- An analysis of the speed-time plot reveals that whenever the following vehicle realises the presence of a leading vehicle within the zone of interaction, it decelerates and begins to follow the leading vehicle, eventually matching its speed [7].

2.2.1 Simulation model

The vehicle generation and analysis processes in this study are derived from the CUTSiM model developed by Maurya (2007). In the vehicle generation phase, vehicles are randomly placed across the entire road width, ensuring appropriate gaps both horizontally and longitudinally between each generated vehicle.

These generated vehicles are assigned various parameters related to the vehicle and driver, such as vehicle type, current speed, risk speed specific to each vehicle type, interaction range, and lateral clearance of vehicles [7].

When there is no leading vehicle directly in front of the following vehicle, the available gap between neighbouring leading vehicles is taken into account. The maximum escape speed (MES) is then calculated based on the minimum lateral gap, considering the potential lateral movement needed for the following vehicle.

2.2.2 Algorithm

The model algorithm consists of input conditions and initialization, different cases to be followed, and the desired output. The user can provide inputs such as driver characteristics, roadway specifications, vehicle attributes, and traffic composition. Based on the given flow and traffic composition, vehicles will be generated [7]. During each iteration of the simulation, which is determined by the user-defined total simulation duration, the position of each vehicle will be updated according to the governing conditions.

2.2.3 Limitation

Scope for simulation model is limited to uninterrupted unidirectional traffic on straight and level mid-block sections.

2.3 Calibration of Car-following model for Indian traffic conditions

The development of car-following models for Indian traffic conditions involved modifying the General Motors (GM) Model and Hidas Model, which are standard car-following models [2]. These modifications were made by calibrating the parameters using data collected from both urban and non-urban corridors. Comparing the RMSE and MAE values between the estimated and observed data indicates that the developed car-following models demonstrate a reasonable level of accuracy in estimating the accelerations of the following vehicles.

2.3.1 Methodology

For this experiment, two categories of road stretches were taken into account: urban corridors and non-urban road corridors. The V-Box equipment was installed in both the leading and following vehicles to track their positions over time. The collected data, consisting of latitude and longitude information from the V-Box equipment, was gathered and extracted for further analysis. The collected data was then analysed to determine the position, speed, and acceleration of both the leading and following vehicles, aligning them based on a common timeframe [2].

2.3.2 Results

This paper contributes to the development of a realistic car-following model specifically designed for Indian traffic conditions. By utilising the modified parameters of the Modified GM model, accurate predictions of driver behaviour can be achieved for both urban and non-urban corridors. The Hidas model shows promising results with relatively low errors, indicating its capability to predict driver behaviour, although it may not be well-suited for Indian conditions. The adoption of such car-following models in transportation policy analysis is crucial. This model enables a better understanding of individual driver behaviour, leading to enhanced accuracy in predicting behaviour and facilitating the evaluation of appropriate transport policies [2].

Chapter 3
Problem Description

A comprehensive depiction of mixed-mode traffic encompasses a variety of road participants, including cars, trucks, motorcycles, pedestrians, and bicycles, as well as diverse traffic situations like urban driving, highway travel, road maintenance, and parking areas. Furthermore, it encompasses various traffic scenarios such as car-following, roundabouts, left-turns, and lane-changing. It is also worth noting that driver behavior and traffic flow can be influenced by weather conditions and the state of the road.

Mixed-mode traffic presents significant challenges in the field of transportation engineering. The complex interactions and heterogeneous characteristics of these modes necessitate a comprehensive understanding of their behavior, impacts, and optimization strategies. Promisingly, there is untapped potential for scientific research on the unique requirements of mixed-mode traffic in developing countries. The system representation of the input data in our traffic simulator is depicted in Figure 3.1 highlighting the retrieval of macroscopic traffic parameters.

This thesis aims to bridge this research gap by undertaking a systematic investigation into the analysis and optimization of mixed-mode traffic, utilizing any traffic simulator as the primary analytical tool. The problem statement for this thesis revolves around examining the means to effectively model, simulate, and analyze mixed-mode traffic, accounting for the multifaceted dynamics, behaviors, and interactions among different transportation modes.

Our research primarily focuses on macroscopic parameters, where the dynamics of individual vehicles are not considered. Instead, we analyze quantities with macroscopic meaning, such as vehicle density $\rho(x,t)$ and average velocity $v(x,t)$, which are both functions of space and time. These quantities are obtained by averaging over a region of sufficiently large spatial extent. In this context, we examine the parameters at a microscopic level, focusing on individual vehicle speed and

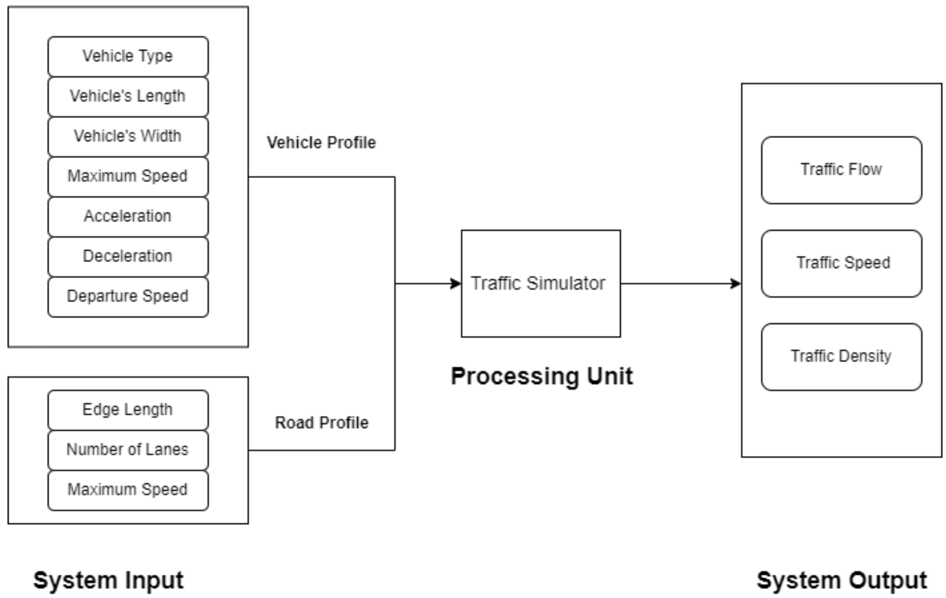


Figure 3.1: System Representation

acceleration. However, for our experiment, we aggregate these values to derive mean speed, traffic flow, and density through temporal and spatial averaging.

Our research endeavor seeks to address the following primary research questions:

1. How can the traffic simulator be suitably customized and configured to accurately represent the intricacies of mixed-mode traffic, encompassing different types of vehicles?

2. Which associated parameters are most appropriate for mixed-mode traffic within the simulation tool, enabling the faithful representation of realistic interactions and movement patterns?

3. How can the macroscopic parameters such as traffic flow, traffic speed, and traffic density be comprehensively evaluated and optimized within the context of mixed-mode traffic scenarios?

Based on the above-mentioned questions, this research aims to study the behaviour of mixed-mode traffic and how different modes of transport interact with each other. After understanding heterogeneous data, we will try to replicate on any traffic simulator and try to observe how it behaves for mixed-mode traffic scenarios. If, any mismatch exists then, we can tune the parameters of traffic simulator to improve the accuracy and reliability for mixed-mode traffic analysis.

In this research, the Root Mean Square Error (RMSE) has been adopted as the evaluation metric for assessing the performance of the mixed-mode traffic model.

It represents the square root of the average of the squared differences between the predicted values and the actual observed values.

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \tag{3.1}$$

In this equation, y_i represents the observed values, $\hat{y}_i$ represents the predicted values, and n represents the total number of data points.

A lower RMSE value indicates a better fit of the model, indicating that the predictions closely align with the observed data. Conversely, a higher RMSE value suggests a larger average discrepancy between the predicted and observed values, indicating less accuracy in the model's predictions.

3.1 Assumptions

The assumptions in this research related to the modeling of mixed-mode traffic are as follows:

- The road conditions are normal, meaning that they do not include any instances of heavy rain, snow, fog, icy roads, or similar adverse weather conditions.
- Traffic data offers accurate information regarding traffic parameters.

CHAPTER 4
Traffic Dataset: Exploration and Analysis

A heterogeneous traffic dataset is essential for analyzing mixed-mode traffic due to the diverse characteristics and behaviors of different vehicle types. By examining a heterogeneous dataset, we can delve into the nuances of speed variations, size disparities, maneuvering capabilities, and traffic flow patterns that arise from the coexistence of these modes. This detailed understanding will be helpful for the development of accurate and realistic traffic models that capture the complexities of mixed-mode traffic scenarios.

In our study, we acquired the HighD dataset [4], a novel collection of naturalistic vehicle trajectories obtained from German highways. This dataset encompasses both cars and trucks. Additionally, our research also incorporated the Chennai dataset [3], which features a diverse range of vehicles including bikes, rickshaws, cars, and heavy vehicles, recorded in Chennai, India. This combination of datasets allowed us to comprehensively analyze and explore various aspects of mixed-mode traffic.

4.1 HighD Dataset

The HighD dataset includes post-processed trajectories of 1,10,000 vehicles including cars and trucks extracted from drone video recordings at German highways around Cologne during 2017 and 2018 [4].

In this dataset, authors have used camera-equipped drones to measure every vehicle's position and movements from an aerial perspective for scenario-based validation. So, a drone was hovering next to German highways and the recordings cover a road segment of about 420 m as displayed in Figure 4.1.

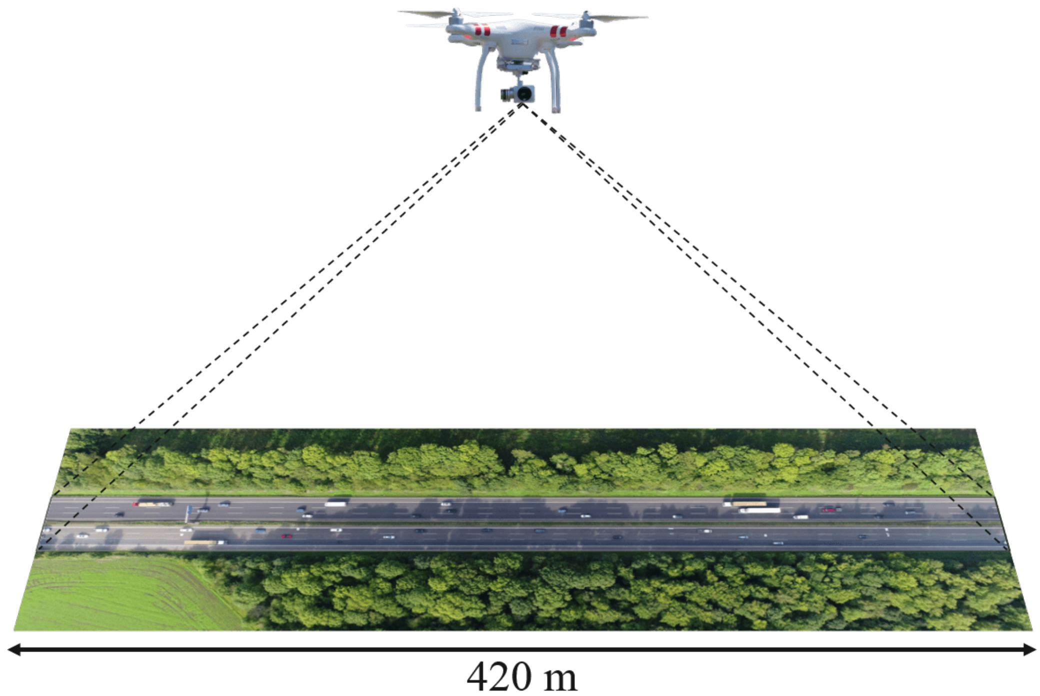


Figure 4.1: Recording Setup on a Road Section with a Length of 420m.

4.1.1 Dataset Format

The dataset includes four files for each recording: an aerial shot of the specific highway area and three CSV files, containing information about the site, the vehicles and the extracted trajectories. Here XX denotes track number for all the tables of dataset.

4.1.2 Recording Meta Information

The first file contains metadata for each recording. The metadata provides a general overview, e.g. of the time of recording, the highway section considered and the total number of vehicles recorded. Below table 4.1 describes about it.

4.1.3 Track Meta Information

A file contains an overview of all tracks. For each track there are summary values like vehicle dimensions, vehicle class, driving direction, the distance covered or the average speed. The purpose of this file is to filter tracks e.g. by class or driving direction mentioned in table 4.2.

No.	Name	Description	Unit
1	id	The id of the recording. Every recording has a unique id.	[-]
2	frame-Rate	The frame rate which was used to record the video.	[hz]
3	location-Id	The id of the recording location. In total six different locations exist in the dataset.	[-]
4	duration	The duration of the recording.	[s]
5	num-Vehicles	The number of vehicles tracked including cars and trucks.	[-]
6	num-Cars	The number of cars tracked.	[-]
7	num-Trucks	The number of trucks tracked.	[-]

Table 4.1: Recording Meta Information (XX_recordingMeta.csv)

No.	Name	Description	Unit
1	id	The id of the recording. The ids are assigned in ascending order.	[-]
2	initial-Frame	The initial frame in which the vehicle track starts.	[-]
3	final-Frame	The frame in which the track of the vehicle ends.	[-]
4	num-Frames	The total lifetime of the track as number of frames.	[-]
5	class	The vehicle class of the tracked vehicle (Car or Truck).	[-]
6	driving-Direction	The driving direction of the vehicle. Either 1 for the left direction (upper lanes) or 2 for the right direction (lower lanes).	[-]
7	traveled-Distance	The distance covered by the track.	[m]
8	minX-Velocity	The minimal velocity in driving direction.	[m/s]
9	maxX-Velocity	The maximal velocity in driving direction.	[m/s]
10	meanX-Velocity	The mean velocity in driving direction.	[m/s]

Table 4.2: Recording Meta Information (XX_TracksMeta.csv)

4.1.4 Track Complete Information

Detailed information like speeds, accelerations, lane positions and a description of surrounding vehicles in every frame are stored for each track in the last file. Table 4.3 summarizes this information.

No.	Name	Description	Unit
1	frame	The current frame.	[-]
2	id	The vehicle's id.	[-]
3	xVelocity	The longitudinal velocity in the image coordinate system..	[m/s]
4	yVelocity	The lateral velocity in the image coordinate system.	[m/s]
5	x-Acceleration	The longitudinal acceleration in the image coordinate system.	[m/s^2]
6	y-Acceleration	The lateral acceleration in the image coordinate system.	[m/s^2]
7	frontSight-Distance	The distance to the end of the recorded highway section in driving direction from the vehicle's center.	[m]
8	backSight-Distance	The distance to the end of the recorded highway section in the opposite driving direction from the vehicle's center.	[m]
9	dhw	The Distance Headway. This value is set to 0, if no preceding vehicle exists.	[m]
10	thw	The Time Headway. This value is set to 0, if no preceding vehicle exists.	[s]
11	ttc	The Time-to-Collision. This value is set to 0, if no preceding vehicle or valid TTC exists.	[s]

Table 4.3: Recording Track Information (XX_tracks.csv)

4.2 Chennai Dataset

4.2.1 Data Collection Site

The video footage was collected on a busy urban road called Maraimalai Adigalar Bridge in Saidapet, Chennai, India [3]. This road consists of six lanes and is designed to separate traffic flows. The data collection specifically focused on the northbound lanes, as depicted in Figure 4.2. The chosen section of the road is situated on a bridge, ensuring a consistent road layout and eliminating potential influences such as nearby intersections, parked vehicles, or bus stops that could impact driver behavior. Moreover, there is a physical barrier segregating the pedestrian walkway, thereby eliminating any interaction between vehicles and pedestrians. The video recording spanned from 10 a.m. to 3:30 p.m. on February 13, 2014. The camera used to capture the footage was positioned on the roof of a building adjacent to the selected road section.

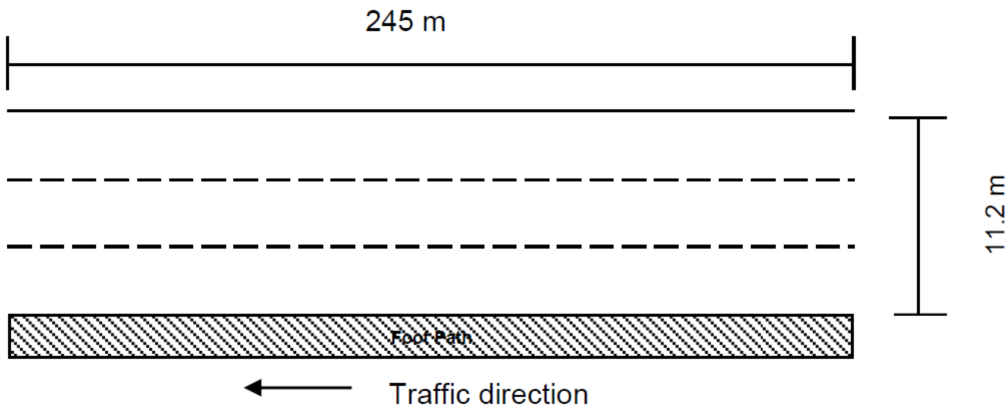


Figure 4.2: Data Collection Site in Chennai, India

4.2.2 Trajectory Extraction and Traffic Flow Characteristics

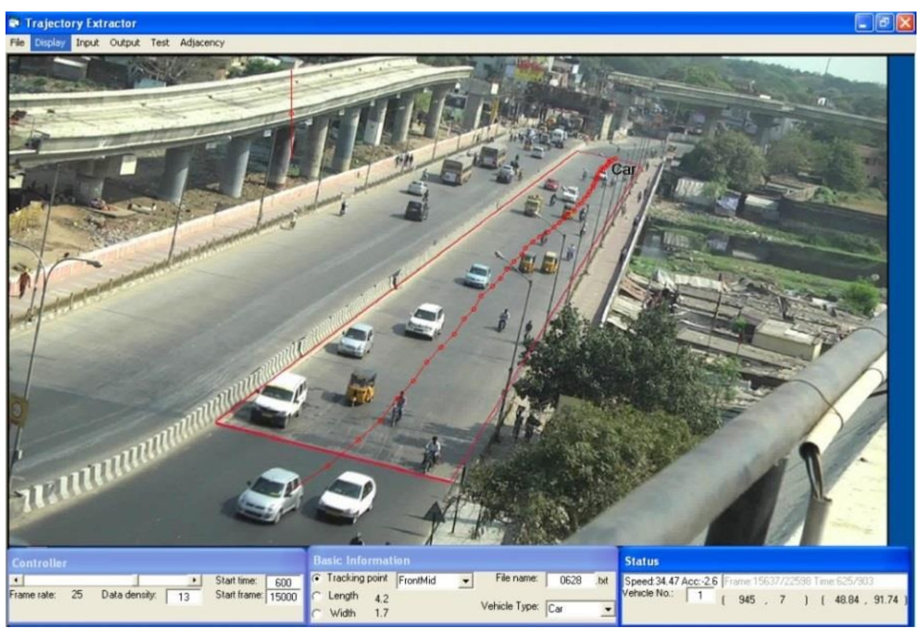


Figure 4.3: Trajectory Extractor User Interface - Road Section and Reference Points

Trajectory Extractor tool was employed to extract relevant information about vehicles from the recorded video sequences [3]. Specifically, the tool was utilized to determine the coordinates, dimensions, and vehicle classification of all the vehicles present within a 30-minute timeframe, ranging from 2:45 PM to 3:15 PM.

To facilitate this process, a user-friendly graphical interface was developed for Windows, enabling a human operator to manually identify vehicle boundaries using a mouse pointer on the screen. The system then converted these identified boundaries into real-world coordinates and calculated the positions, speeds, and accelerations of the vehicles. The conversion of coordinates relied upon four reference points within the video images and their corresponding coordinates in the real world. Figure 4.3 illustrates the graphical user interface of the software, showcasing an image of the road section under study along with the rectangular shape formed by the four reference points.

The dataset obtained from the study comprises 3005 trajectories of vehicles. These trajectories were recorded at a resolution of 0.5 seconds, resulting in a total of 111,629 observations. The presence of mixed traffic flow introduces distinctive characteristics that set it apart from homogeneous traffic. This aspect is clearly evident in the collected data, where passenger cars accounted for only 26.6% of the vehicles in the traffic flow. In contrast, motorcycles represented 56.4% of the vehicles, auto-rickshaws accounted for 12.2%, and heavy vehicles, including light and heavy trucks as well as buses, made up 4.8% of the total. Table 4.4 summarizes the information.

Vehicle Type	Mean Flow	Mean Speed	Mean Density	Maximum Acceleration	Maximum Deceleration
Motorcycle	3390	6.01	49.34	4.734	4.659
Car	1600	6.13	23.46	4.436	4.371
Auto-Rickshaw	732	5.06	13.24	4.501	4.340
Heavy Vehicles	288	5.64	4.78	3.981	4.208
All Types	6010	5.88	90.81	4.734	4.659

Table 4.4: Longitudinal Traffic Flow Characteristics of the Collected Data

CHAPTER 5

Experiments and Results

5.1 Simulation Environment

To address the complexities and challenges in transportation, researchers and practitioners have turned to advanced simulation tools that can accurately model and analyze different traffic parameters, and assess the impact of various transportation strategies. In this context, SUMO (Simulation of Urban Mobility) Eclipse [6] emerges as a powerful software tool that offers a comprehensive platform for traffic simulation and analysis.

SUMO Eclipse is an extension of an open-source microscopic traffic simulation package widely recognized for its scalability, flexibility, and accuracy. By integrating SUMO's capabilities with the Eclipse Integrated Development Environment (IDE), SUMO provides an intuitive and user-friendly interface, making it accessible to both researchers and transportation professionals for conducting in-depth traffic studies and enhancing decision-making processes.

This thesis aims to delve into the functionalities and applications of SUMO, exploring its potential as a reliable tool for analyzing mixed-mode transportation systems by using it as the comprehensive platform which enables it as an accurate modeling and simulation tool of complex traffic scenarios, including mixed vehicle types and varying traffic volumes.

In our research, we have employed version 1.14 of the SUMO as our primary tool for traffic simulation and analysis. Additionally, for the creation and editing of the network file, we have utilized version 1.14 of NETEDIT [1]. Similarly, we write route file and information about loop detectors, bus-stops etc. in additional file.

[1] https://sumo.dlr.de/docs/Netedit/index.html

5.2 HighD Simulation Scenario Setup

To conduct a comprehensive simulation using the "The highD Dataset" in SUMO, the following setup is proposed:

Step 1: Data Preparation (HighD Dataset)

- Obtain the HighD dataset, which includes the necessary information for simulating mixed-mode traffic. This dataset consists of real-world traffic data captured from diverse vehicle types.
- After obtaining the dataset, we have understood the dataset structure, attributes, and available information, such as vehicle trajectories, vehicle types, and timestamps.

Step 2: SUMO Installation and Configuration

- Download and install SUMO Eclipse, ensuring compatibility with your operating system. Configure SUMO by specifying the necessary parameters, such as simulation time, simulation step size, and network properties.
- After understanding the dataset, we identify the necessary attributes and import the HighD dataset into SUMO, ensuring the dataset is in a compatible XML format.

Step 3: Network Design and Generation

- Design the road network based on the HighD dataset using the “netedit” file. This involves creating roads, and lanes, and defining connectivity between them.
- Utilize the available information in the HighD dataset to accurately represent the road network in SUMO. Ensure proper positioning of road geometry, and lane configurations.
- To monitor the traffic flow of cars and trucks, strategically place loop detectors along the road. This placement has been specified in the "additional.xml" file, which serves as an input file to the configuration file (sumo.cfg) to incorporate additional features within the SUMO simulation.
- Generate the network using SUMO, taking into account the HighD dataset’s spatial attributes and road topology.

Step 4: Vehicle Definition and Assignment

- Define the vehicle types present in the HighD dataset within SUMO. This includes specifying attributes such as vehicle ID, vehicle length, vehicle width, maximum speed, acceleration, and depart speed in the "route.xml" [2] file.
- Assign the vehicle types to the corresponding vehicles in the HighD dataset, ensuring an accurate representation of the mixed-mode traffic.
- Ensure proper vehicle insertions by setting the departure times for each vehicle based on the recorded trajectories from the HighD dataset.

Step 5: Integrating Scenario files and Simulation Execution

- The sumo.cfg file is a configuration file used in SUMO to customize the simulation settings and behavior. It contains a range of parameters that control various aspects of the simulation such as time step size, output file formats, and simulation duration. Users can modify the values in the sumo.cfg file to adjust simulation-specific parameters, including network and vehicle properties, traffic demand, traffic light behavior, emission models, and visualization options. This file allows for fine-tuning the simulation environment to match specific scenarios and research objectives. By appropriately configuring the sumo.cfg file, users can create accurate simulations that accurately represent real-world traffic conditions. These required scenario files for HighD dataset can be referred from the Appendix A.
- Execute the simulation in SUMO, by specifying the input files, output files, and desired simulation duration in the "sumo.cfg" file.

The road built in SUMO, which is shown in below figure 5.1, is a freeway that consists of two lanes in each direction. The total length of the road is 420 meters. The figure also indicates car-following simulation models of cars and trucks, represented by yellow and red symbols, respectively.

In this analysis, we measure the traffic flow, traffic density, and traffic speed. Our analysis is done with a time interval of 60 seconds with a displacement of 5 seconds between intervals. E.g. (0-60 sec), (5-65 sec), (10-70 sec), and so on.

We have a road segment length of 420m. So, traffic flow is calculated at D=100m, D=200m, D=300m, and D=400m by counting the number of vehicles crossing

[2] https://sumo.dlr.de/docs/Definition_of_Vehicles%2C_Vehicle_Types%2C_and_Routes.html

Figure 5.1: HighD Road Simulation Snapshot

these observational points during minute intervals. This data set is generated by camera-equipped drones to measure every vehicle's position and movements from an aerial perspective. Therefore, we have considered 4 different observational points to measure the traffic flow.

In a similar way, traffic speed and traffic density are measured for the entire road segment. Traffic speed is measured by aggregating the speed of all the vehicles present on the road segment during one-minute of intervals. Similarly, Traffic density indicates the count of vehicles present on the road segment during minute intervals.

In our research, we have analyzed the dataset for tracks: 1, 3, 5, and 9. The below tracks are representative of traffic conditions on all the tracks in the dataset. The table 5.1 below represents the summary of all the tracks.

Track No	Cars	Trucks	Total Vehicles	Duration(s)	% Cars	% Trucks	Ratio
1	316	85	401	902	78.80	21.02	3.72
3	290	104	394	1010	73.60	26.40	2.79
5	430	132	562	1140	76.51	23.49	3.26
9	474	104	578	1070	82.01	17.99	4.56

Table 5.1: Summary of all tracks

Parameter	Unit	RMSE	% RMSE	Mean Error
Flow	Total Flow @ 100m	2.15	7.51	0.23
	Car Flow @ 100m	1.82	8.18	0.17
	Truck Flow @ 100m	0.82	13.48	0.06
	Total Flow @ 400m	1.55	5.41	0.09
	Car Flow @ 400m	1.44	6.44	0.08
	Truck Flow @ 400m	0.71	11.49	0.01
Speed	Total Density	5.83	20.76	4.88
	Density of Car	4.47	20.32	3.50
	Density of Truck	1.90	30.91	0.91
Density	Total Speed	5.21	15.95	5.14
	Speed of Car	5.00	14.31	4.88
	Speed of Truck	8.69	35.85	6.83

Table 5.2: Aggregate Error in all Tracks-V1

5.2.1 Result Analysis

We have written Python scripts to process the simulator output and compare the macroscopic parameters (Aggregate flow, speed, density) with the data set using the Root Mean Square Error (RMSE) as metric.

We utilized a Python script to export SUMO's simulation output data (fcd.xml) into a compatible CSV format, containing crucial information like vehicle trajectories and speeds. All the required python files can be accessed through Code Repository.

Data Preprocessing in Python:

- Import the simulation output data into Python using appropriate modules (e.g. CSV)

Comparison of Simulation Results:

- Write Python scripts to perform the desired comparison analysis, such as comparing simulated vehicle speeds against observed speeds or evaluating traffic flow patterns.
- Visualize comparison results through line plots to gain insights into simulation-observed data similarities and differences.
- Utilize statistical measures Root Mean Squared Error (RMSE) to quantify the accuracy of the simulation compared to observed data.

Parameter	Unit	RMSE	% RMSE	Mean Error
Flow	Total Flow @ 100m	3.07	10.59	0.13
	Car Flow @ 100m	2.61	11.52	0.10
	Truck Flow @ 100m	1.11	18.13	0.03
	Total Flow @ 400m	3.48	12.06	0.09
	Car Flow @ 400m	3.01	13.32	0.07
	Truck Flow @ 400m	1.14	18.98	0.08
Speed	Total Density	7.43	26.36	6.09
	Density of Car	5.53	25.11	4.25
	Density of Truck	2.50	40.71	1.81
Density	Total Speed	1.85	5.70	-1.25
	Speed of Car	2.16	6.20	-1.34
	Speed of Truck	1.46	6.05	0.80

Table 5.3: Aggregate Error in all Tracks-V2

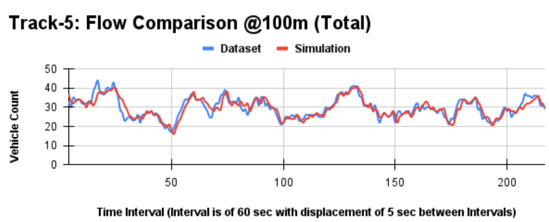
Upon conducting the initial SUMO simulation using its default parameters for the given HighD dataset, we observe distinct aggregate results for tracks 1, 3, 5, and 9. Throughout this simulation, SUMO utilizes the default acceleration values of 2.6 m/s^2 for cars and 1.3 m/s^2 for trucks. However, this default configuration leads to a substantial deviation in traffic speeds. The above table 5.2 illustrates these findings, revealing notable disparities in traffic density and speed when compared to the dataset, despite achieving a reasonable traffic flow alignment.

By rerunning the simulation using the precise acceleration values specified in the dataset (1.13 m/s^2 for cars and 0.25 m/s^2 for trucks), we achieve traffic speed that closely aligns with the dataset. However, notable disparities arise in traffic flow and density, as depicted in the table 5.3 above. These variations in flow and density appear from the presence of vehicles positioned at intermediate locations along the 0m to 400m road stretch, thereby altering the vehicle count and density measurements.

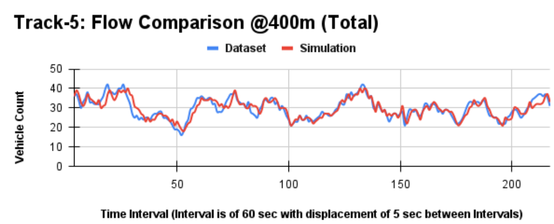
Now, to mitigate the influence of initial conditions, we eliminate vehicles positioned within the 0m to 400m range on the road stretch. This ensures an accurate count of vehicles traversing the entire road segment. Subsequently, we rerun the SUMO simulation, incorporating the dataset's specified acceleration values (1.13 m/s^2 for cars and 0.25 m/s^2 for trucks). We then plot graphs depicting the traffic flow, density, and speed for tracks 1, 3, 5, and 9, demonstrating the extent to which the simulation output aligns with the dataset provided.

5.2.2 Track-5 (Experimental Results)

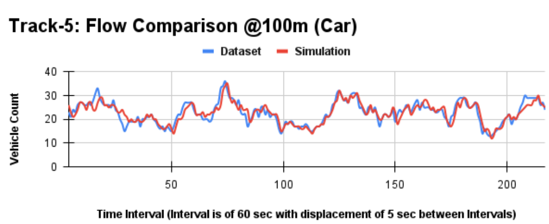
In this section, we have included the graphical results of track 5, while the graphs for the other tracks (Track No: 1, 3, 9) have been incorporated in Appendix A. Readers can refer to the appendix for a comprehensive view of the simulation results across all tracks. Additionally, we have presented a detailed tabulation of the simulation results for each track in the discussion, providing a comprehensive analysis of the findings. All the results are presented as percentages of RMSE.



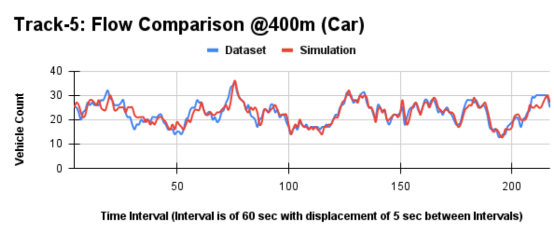
(a) RMSE of Total Vehicles'Flow at 100m: 8.14 with Mean Error of -0.05



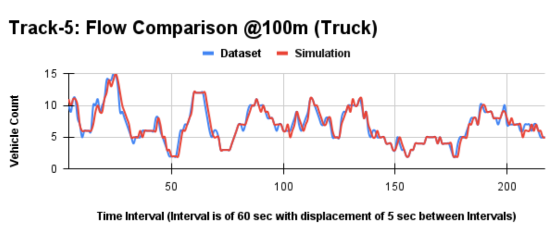
(b) RMSE of Total Vehicles'Flow at 400m: 8.07 with Mean Error of -0.06



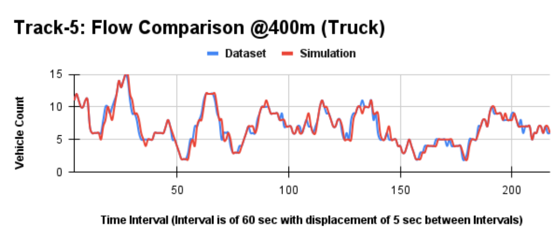
(c) RMSE of Total Cars'Flow at 100m: 9.16 with Mean Error of -0.06



(d) RMSE of Total Cars'Flow at 400m: 9.33 with Mean Error of -0.06



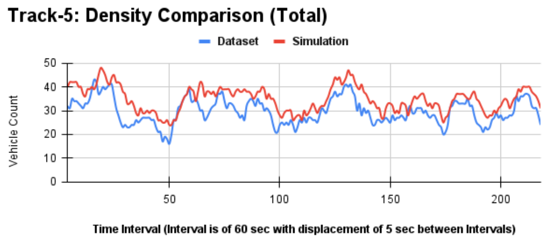
(e) RMSE of Total Trucks'Flow at 100m: 11.31 with Mean Error of 0.01



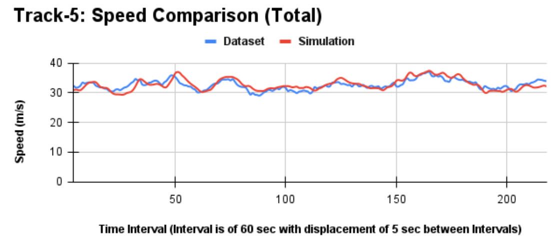
(f) RMSE of Trucks'Flow at 400m: 10.38 with Mean Error of 0

Figure 5.2: Flow Results of Track-5

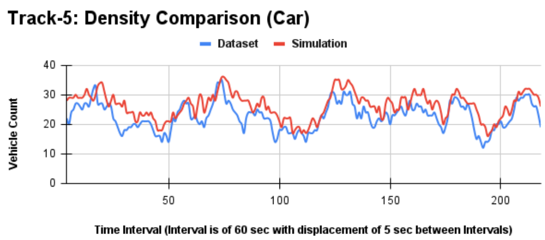
Upon analyzing the graphs shown in figure 5.2, it becomes evident that the traffic flow at both 100 meters and 400 meters exhibits a close resemblance to the simulation model. This suggests that the simulation model is effectively capturing the dynamics of traffic flow in the given scenarios, leading to reliable and accurate results.



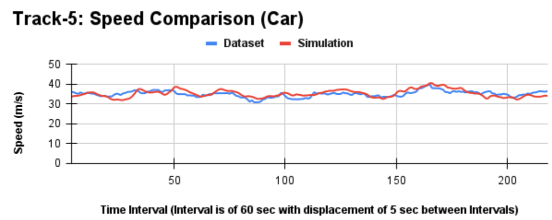
(a) RMSE of Total Density: 20.91 with Mean Error of 5.20



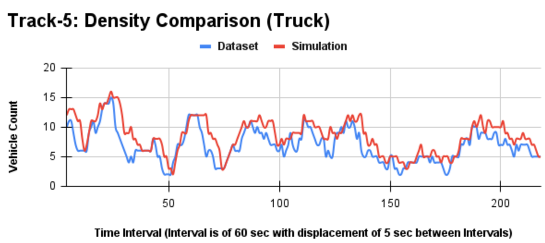
(b) RMSE of Total Speed: 3.85 with Mean Error of 0.13



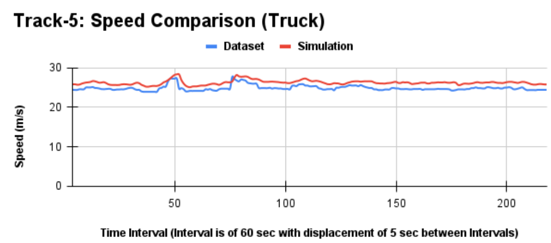
(c) RMSE of Car Density: 20.16 with Mean Error of 3.62



(d) RMSE of Car Speed: 4.55 with Mean Error of 0.29



(e) RMSE of Truck Density: 32.73 with Mean Error of 1.58



(f) RMSE of Truck Speed: 5.79 with Mean Error of 1.38

Figure 5.3: Speed and Density Results of Track-5

Based on the presented findings, it is evident from figure 5.3 that traffic density does not exhibit a strong correlation with the dataset and yields a significant level of error, particularly for trucks. However, it is noteworthy that traffic speed demonstrates a close match with the dataset. These results suggest that the simulation model effectively captures the dynamics of traffic speed but faces challenges in accurately representing traffic density, especially for heavy vehicles. Further investigation and refinement of the model parameters may be necessary to improve the accuracy of traffic density predictions.

The simulation results shown in table 5.5 for Track-1 exhibit a strong alignment with traffic flow and speed, while showing significant deviation in traffic density. This discrepancy could potentially come from the simplified assumptions made by SUMO, which may not fully capture complexities of real-world traffic

Parameter	Unit	RMSE	% RMSE	Mean Error
Flow	Total Flow @ 100m	2.42	8.14	-0.05
	Car Flow @ 100m	2.09	9.16	-0.06
	Truck Flow @ 100m	0.78	11.31	0.01
	Total Flow @ 400m	2.40	8.07	-0.06
	Car Flow @ 400m	2.13	9.33	-0.06
	Truck Flow @ 400m	0.72	10.38	0.00
Speed	Total Density	6.20	20.91	5.20
	Density of Car	4.59	20.16	3.62
	Density of Truck	2.25	32.73	1.58
Density	Total Speed	1.26	3.85	0.13
	Speed of Car	1.59	4.55	0.29
	Speed of Truck	1.44	5.79	1.38

Table 5.4: Error Noted in Track-5

Parameter	Unit	RMSE	% RMSE	Mean Error
Flow	Total Flow @ 100m	2.22	8.17	-0.06
	Car Flow @ 100m	1.94	9.01	-0.02
	Truck Flow @ 100m	0.72	12.89	-0.04
	Total Flow @ 400m	2.80	10.33	-0.06
	Car Flow @ 400m	2.42	11.10	-0.02
	Truck Flow @ 400m	0.75	14.16	-0.04
Speed	Total Density	6.30	23.18	5.07
	Density of Car	4.90	22.77	3.76
	Density of Truck	1.94	34.43	1.31
Density	Total Speed	2.06	6.44	-1.39
	Speed of Car	2.20	6.47	-1.16
	Speed of Truck	2.48	10.72	0.29

Table 5.5: Error Noted in Track-1

dynamics. Further investigation is required to explore the underlying factors contributing to this mismatch between simulated and actual traffic density.

The error analysis presented in Table 5.6 reveals discrepancies in traffic flow, speed, and density. It is evident that the match between simulated and observed flow is not ideal. Furthermore, there is a notable mismatch for traffic density, indicating a significant deviation from the given dataset. On the other hand, the traffic speed demonstrates a close alignment with the provided dataset, showcasing a strong match.
The error analysis presented in Table 5.7 reveals discrepancies in traffic flow, speed, and density. It is evident that the match between simulated and observed flow is not ideal. Furthermore, there is a notable mismatch for traffic density, indicating a

Parameter	Unit	RMSE	% RMSE	Mean Error
Flow	Total Flow @ 100m	1.68	7.17	-0.02
	Car Flow @ 100m	1.51	8.81	-0.02
	Truck Flow @ 100m	0.61	9.68	0.01
	Total Flow @ 400m	1.94	8.29	-0.01
	Car Flow @ 400m	1.73	10.14	-0.01
	Truck Flow @ 400m	0.6	9.46	0.01
Speed	Total Density	5.48	23.37	4.68
	Density of Car	3.88	22.62	3.04
	Density of Truck	2.04	32.40	1.63
Density	Total Speed	2.38	7.53	-2.02
	Speed of Car	2.8	8.09	-2.23
	Speed of Truck	0.42	1.78	0.30

Table 5.6: Error Noted in Track-3

Parameter	Unit	RMSE	% RMSE	Mean Error
Flow	Total Flow @ 100m	3.12	9.65	0.28
	Car Flow @ 100m	3.01	11.36	0.24
	Truck Flow @ 100m	0.80	13.65	0.04
	Total Flow @ 400m	3.40	10.42	0.22
	Car Flow @ 400m	3.22	12.03	0.19
	Truck Flow @ 400m	0.67	11.37	0.03
Speed	Total Density	7.21	22.36	6.04
	Density of Car	5.97	22.58	4.68
	Density of Truck	1.84	31.66	1.37
Density	Total Speed	1.21	3.55	-0.75
	Speed of Car	1.25	3.47	-0.76
	Speed of Truck	1.53	6.03	1.30

Table 5.7: Error Noted in Track-9

significant deviation from the given dataset. On the other hand, the traffic speed demonstrates a close alignment with the provided dataset, showcasing a strong match.

5.2.3 Aggregate Results

The results indicate a close correspondence between simulated traffic flow and speed with the dataset. However, a noticeable disparity persists in the measurement of traffic density and this can be seen in the below table 5.8.

The table demonstrates a strong correspondence between the simulated and dataset values for traffic flow and speed. However, a notable mismatch is evident in traffic density, despite our efforts to tune the acceleration values according to the dataset.

Parameter	Unit	RMSE	% RMSE	Mean Error
Flow	Total Flow @ 100m	2.36	8.28	-0.03
	Car Flow @ 100m	2.14	9.59	-0.03
	Truck Flow @ 100m	0.73	11.88	-0.01
	Total Flow @ 400m	2.64	9.28	-0.03
	Car Flow @ 400m	2.37	10.65	-0.02
	Truck Flow @ 400m	0.69	11.34	-0.01
Speed	Total Density	6.30	22.46	3.74
	Density of Car	4.83	22.03	2.61
	Density of Truck	2.02	32.81	1.13
Density	Total Speed	1.73	5.34	-0.82
	Speed of Car	1.96	5.64	-0.78
	Speed of Truck	1.47	6.08	0.49

Table 5.8: Aggregate Error in all Tracks-V3

This discrepancy may come from internal factors within SUMO that inadequately capture the complexity of mixed-mode traffic scenarios. Further investigation is needed to gain deeper insights into the underlying causes of this mismatch.

5.3 Chennai Simulation Scenario Setup

To conduct a comprehensive simulation using the "Trajectory Data and Flow Characteristics of Mixed Traffic" dataset in SUMO, the following setup is proposed:

1. Dataset Preparation: Obtain the "Trajectory Data and Flow Characteristics of Mixed Traffic" dataset compatible with SUMO. Then, we understand the dataset structure, its attributes, and available information, such as vehicle trajectories and types.

2. SUMO Network Design: We create a realistic road network layout in SUMO, representing the actual road infrastructure where the data was collected. Define roads and lanes. Align the network design with the dataset information to accurately model the road layout.

3. Vehicle Definition: Define vehicle types based on the mixed traffic composition in the dataset. Specify attributes such as maximum speed, acceleration, and deceleration for each vehicle type and the route file is generated using traffic parameters obtained from the table 4.4 for all the vehicles.

4. Simulation Execution: Configure simulation parameters including time step, inputs and outputs. Import the trajectory data into SUMO, associating each trajectory with the corresponding vehicle type. Now, to generate the scenario for this data set, we have used the Sub-lane model of SUMO. In this model, the road network's standard lanes are subdivided into smaller sub-lanes, each having a minimum width determined by the specified resolution (–lateral-resolution) provided in sumo.cfg file and it can be referred from the Appendix B. The resolution, which serves to implicitly divide a lane into one or more sub-lanes, defines the granularity of decision making and collision detection.Vehicles are assigned to one or multiple sub-lanes, and car-following calculations are conducted for all vehicles that are being followed on at least one sub-lane. To illustrate, when a car is following two motorcycles, it must account for the presence and movements of both motorcycles in its car-following behavior. We can refer for further details about the sub-lane model. [3]

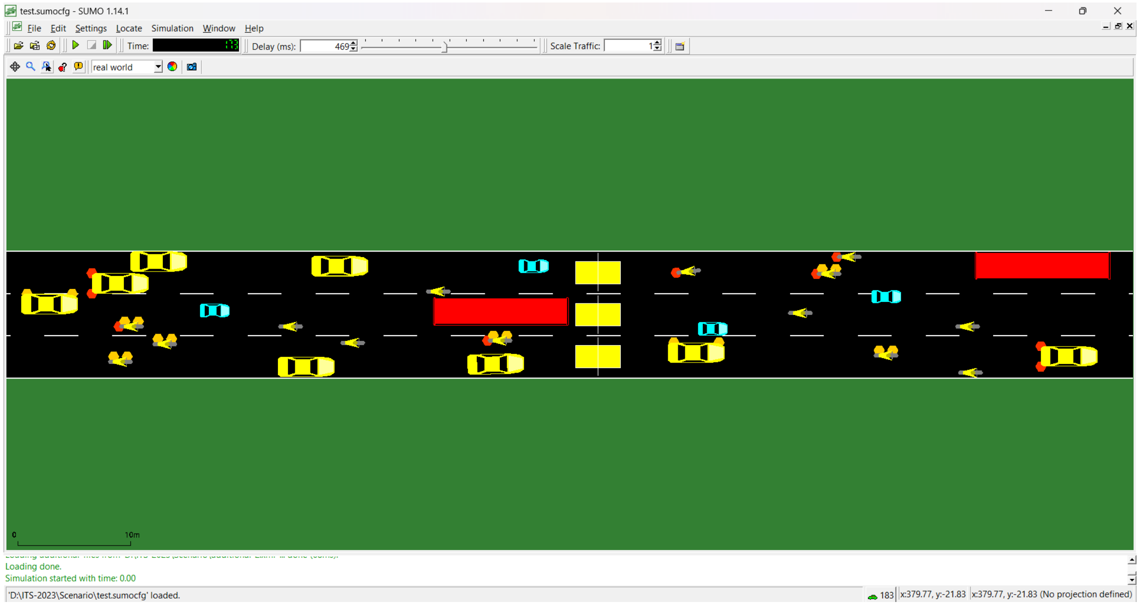


Figure 5.4: Chennai Road Simulation Snapshot

5.3.1 Simulation Results

The road built in SUMO, which is shown in above figure 5.4, is a bridge that consists of three lanes. In our simulation, the road spans a total length of 735 meters. To ensure accurate observations, we allocated the initial 245 meters as a warm-up space before starting data collection. Loop detectors were strategically positioned at the 370-meter mark, to capture vehicle counts. The simulation was run for a duration of 5400 seconds, with observations focused specifically on the period from 1800 to 3600 seconds, thereby excluding any potential noise data from the experiment. The diagram 5.4 showcases distinct car-following simulation models for various vehicle types, including mopeds (light yellow), rickshaws (purple), cars (yellow), and buses (red).
Upon conducting the SUMO simulation, we observe a remarkable correspondence between the simulated traffic flow (vehicles/hr) and the dataset. The table 5.9 below showcases the percentage of error for traffic flow between the dataset and simulation results. Notably, we observe a mere 3.49% error in traffic flow across all vehicle types, with 4.37% for motorcycles, 3.75% for cars, and 1.39% for heavy vehicles. It is also worth mentioning the near-perfect accuracy, with almost 0.27% error, in the case of auto-rickshaws.

Table 5.11 presents the percentage of error for traffic speed (m/s) between the dataset and simulation results. Notably, there is a substantial disparity between

[3] https://sumo.dlr.de/docs/Simulation/SublaneModel.html

Vehicle Type	Mean Flow (veh/hr)	SUMO Flow (veh/hr)	% of Error
Motorcycle	3390	3242	4.37
Car	1600	1540	3.75
Auto-Rickshaw	732	734	-0.27
Heavy Vehicles	288	284	1.39
All types	6010	5800	3.49

Table 5.9: Aggregate Flow Analysis

Vehicle Type	Density (veh/km/lane)	SUMO Density (veh/km/lane)	% of Error
Motorcycle	49.34	31.48	36.20
Car	23.46	15.6	33.50
Auto-Rickshaw	13.24	7.8	41.09
Heavy Vehicles	4.78	3.45	27.82
All types	90.81	58.33	35.77

Table 5.10: Aggregate Density Analysis

the simulation and actual dataset when examining the speed values. The error in speed across all vehicle types is 19.05%, with motorcycles and cars exhibiting errors of 20.13% and 14.19%, respectively. However, heavy vehicles display a relatively lower error of 6.84%, while rickshaws have a significantly higher error of 24.11%, indicating a notable deviation from the expected values.

Vehicle Type	Speed (m/s)	SUMO Speed (m/s)	% of Error
Motorcycle	6.01	7.22	20.13
Car	6.13	7	14.19
Auto-Rickshaw	5.06	6.28	24.11
Heavy Vehicles	5.64	6.59	6.84
All types	5.88	7	19.05

Table 5.11: Aggregate Speed Analysis

The table 5.10 above summarizes the percentage of error in traffic density (veh/km/lane) between the dataset and simulation results. The simulation results show a substantial 35.77% error in density across all vehicle types, with motorcycles and cars exhibiting errors of 36.20% and 33.50%, respectively. Heavy vehicles have a lower error of 27.82% in density, while rickshaws show a higher error of 41.09%.

Overall, the simulation aligns well with the dataset in terms of traffic flow, but there is notable disparity in traffic speed and substantial deviation in traffic density.

CHAPTER 6

Conclusion and Future Work

6.1 Conclusion

In our research, we studied the mixed-mode traffic flow and how it can interact with different modes of transport. We first conducted a literature review to identify the relevant research on mixed-mode traffic that how the concepts have been borrowed from hydrodynamic models. Later on, we tried to replicate the mixed-mode traffic on a traffic simulator called SUMO. To replicate, we developed simulation scenarios for HighD and Chennai data sets of a mixed-mode traffic system. The HighD dataset predominantly includes cars and trucks, characterized by high speeds approaching free flow conditions, but somewhat distant from representing true heterogeneous traffic. On the other hand, the Chennai dataset encompasses motorcycles, rickshaws, cars, and heavy vehicles, where vehicles maintain typical speeds and encounter dense traffic flow. Therefore, all vehicles must adhere to their respective leading vehicles to ensure safe navigation which implies that this dataset accurately depicts the essence of mixed-mode traffic. We conducted a series of simulations to study the impact of different factors on the performance of the system. Later on, we tuned the relevant traffic parameters of the simulation model to optimize the error between the simulated and real-world data.

Our results showed that the SUMO can be used to effectively model mixed-mode traffic. The simulation successfully replicated the traffic flow from the HighD dataset, exhibiting a 10% root mean square error (RMSE) with very less mean error of -0.03. However, disparities were observed in traffic density, with RMSE percentages of 22.46% for all vehicle types, 22.03% for cars, and 32.81% for trucks compared to the HighD dataset with the significant mean error of 3.74. On the other hand, the simulation demonstrated a favorable match with the dataset in terms of traffic speed, with RMSE percentages of 5.34% for all vehicle types, 5.64% for cars, and 6.08% for trucks with very small mean error of -0.82.

Similarly, our simulation of the Chennai dataset demonstrated a high level of consistency in terms of traffic flow, with a minimal 3.49% error rate across all vehicles. However, there were notable disparities in traffic speed, showing a 19.05% error rate across all vehicles, and significant deviations in traffic density, exhibiting a 35.7% error rate across all vehicles.

6.2 Future Work

In the simulation setup for the HighD and Chennai scenarios, the car-following parameters of mixed-mode traffic were manually tuned in SUMO. However, it was noted that certain macroscopic parameters, such as traffic density, did not align closely with the dataset. So, this opens up possibilities for using machine learning models to predict the parameters, offering potential improvements in simulation accuracy. In future work, it would be interesting to explore the use of machine learning to automate the calibration of simulation parameters:

- This would allow for the automatic optimization of simulation parameters, which could lead to significant savings in time and resources.
- We can apply machine learning to the analysis of simulation results and this can be used to identify trends and patterns in simulation data or to predict the behavior of the system under different vehicles distribution and traffic conditions.

References

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Chapter A

Simulation Files of SUMO for HighD dataset

A.1 Road Network File

```
<?xml version="1.0" encoding="UTF-8"?>
<net version="1.9" junctionCornerDetail="5" limitTurnSpeed="5.50" xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" xsi:noNamespaceSchemaLocation="http://sumo.dlr.de/xsd/net_file.xsd">
    <location netOffset="0.00,0.00" convBoundary="-34.69,91.08,80.88,91.18" origBoundary="-10000000000.00,-10000000000.00,10000000000.00,10000000000.00" projParameter="!"/>

    <edge id="-E0" from="J3" to="J2" priority="1" spreadType="roadCenter" length="500.00">
        <lane id="-E0_0" index="0" speed="70.00" length="500.00" shape="80.88,95.98 -34.69,95.88"/>
        <lane id="-E0_1" index="1" speed="70.00" length="500.00" shape="80.88,92.78 -34.69,92.68"/>
    </edge>
    <edge id="E0" from="J2" to="J3" priority="1" spreadType="roadCenter" length="500.00">
        <lane id="E0_0" index="0" speed="70.00" length="500.00" shape="-34.69,86.28 80.88,86.38"/>
        <lane id="E0_1" index="1" speed="70.00" length="500.00" shape="-34.69,89.48 80.88,89.58"/>
    </edge>

    <junction id="J2" type="dead_end" x="-34.69" y="91.08" incLanes="-E0_0 -E0_1" intLanes="" shape="-34.69,91.08 -34.70,97.48 -34.69,91.08"/>
    <junction id="J3" type="dead_end" x="80.88" y="91.18" incLanes="E0_0 E0_1" intLanes="" shape="80.88,91.18 80.89,84.78 80.88,91.18"/>
```

```
</net>
```

A.2 Route File

The Python script was utilized to generate individual route files for each track. An example of such a route file, specifically for track 5, with some vehicle IDs. This process involved the execution of a detailed Python code (1.csv_to_xml.py), which is conveniently accessible for reference and can be retrieved from a designated Code Repository

```
<?xml version='1.0' encoding='utf-8'?>
<routes><vType id="Car" sigma="0.5" maxSpeed="57.97" accel="1.3" speedDev="0.04" color="1,1,0" />
<vType id="Truck" sigma="0.5" maxSpeed="39.6" accel="0.33" speedDev="0.03" color="1,0,0" />
<vehicle id="1" type="Car" length="4.35" width="1.72" depart="4.76" departSpeed="39.76" angle="0" maxSpeed="41.33" departLane="random"><route edges="E0" />
</vehicle><vehicle id="2" type="Truck" length="16.57" width="2.5" depart="6.36" departSpeed="23.66" angle="0" maxSpeed="24.18" departLane="random"><route edges="E0" />
</vehicle><vehicle id="3" type="Car" length="4.85" width="1.92" depart="7.56" departSpeed="23.06" angle="0" maxSpeed="24.01" departLane="random"><route edges="E0" />
</vehicle><vehicle id="4" type="Car" length="4.65" width="2.02" depart="7.76" departSpeed="36.09" angle="0" maxSpeed="37.11" departLane="random"><route edges="E0" />
</vehicle><vehicle id="5" type="Truck" length="14.15" width="2.5" depart="8.8" departSpeed="23.37" angle="0" maxSpeed="23.72" departLane="random"><route edges="E0" />
</vehicle><vehicle id="6" type="Car" length="5.05" width="2.02" depart="9.48" departSpeed="37.79" angle="0" maxSpeed="38.71" departLane="random"><route edges="E0" />
</vehicle><vehicle id="7" type="Car" length="4.55" width="1.92" depart="10.84" departSpeed="35.0" angle="0" maxSpeed="35.96" departLane="random"><route edges="E0" />
</vehicle><vehicle id="8" type="Car" length="5.15" width="2.02" depart="11.12" departSpeed="38.69" angle="0" maxSpeed="40.1" departLane="random"><route edges="E0" />
</vehicle><vehicle id="9" type="Car" length="4.35" width="1.92" depart="14.56" departSpeed="33.83" angle="0" maxSpeed="34.41" departLane="random"><route edges="E0" />
```

A.3 Configuration Files

```xml
<?xml version="1.0" encoding="UTF-8"?>
<configuration xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" xsi:noNamespaceSchemaLocation="http://sumo.dlr.de/xsd/sumoConfiguration.xsd">
    <input>
        <net-file value="HighD.net.xml"/>
        <additional-files value="additional.xml"/>
        <route-files value="routefile.xml"/>
    </input>
    <time>
        <begin value="0"/>
        <end value="1000"/>
    </time>
    <output>
        <fcd-output value="fcd.xml"/>
        <fcd-output.acceleration value="true"/>
        <fcd-output.max-leader-distance value="360.0"/>
    </output>
</configuration>
```

A.4 Additional Files

```xml
<?xml version="1.0" encoding="UTF-8"?>
<additional xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" xsi:noNamespaceSchemaLocation="http://sumo.dlr.de/xsd/additional_file.xsd">
    <!-- Detectors -->
    <e1Detector id="e1" lane="E0_0" pos="100.00" period="5.00" file="e1.xml"/>
    <e1Detector id="e1_car" lane="E0_0" pos="100.00" period="5.00" file="e1_car.xml" vTypes="Car"/>
    <e1Detector id="e1_truck" lane="E0_0" pos="100.00" period="5.00" file="e1_truck.xml" vTypes="Truck"/>
    <e1Detector id="e2" lane="E0_0" pos="200.00" period="5.00" file="e2.xml"/>
    <e1Detector id="e2_car" lane="E0_0" pos="200.00" period="5.00" file="e2_car.xml" vTypes="Car"/>
    <e1Detector id="e2_truck" lane="E0_0" pos="200.00" period="5.00" file="e2_truck.xml" vTypes="Truck"/>
```

```
    <e1Detector id="e3" lane="E0_0" pos="300.00" period="5.00" file="e3.xml"/>
    <e1Detector id="e3_car" lane="E0_0" pos="300.00" period="5.00" file="e3_car.xml" vTypes="Car"/>
    <e1Detector id="e3_truck" lane="E0_0" pos="300.00" period="5.00" file="e3_truck.xml" vTypes="Truck"/>
    <e1Detector id="e4" lane="E0_0" pos="400.00" period="5.00" file="e4.xml"/>
    <e1Detector id="e4_car" lane="E0_0" pos="400.00" period="5.00" file="e4_car.xml" vTypes="Car"/>
    <e1Detector id="e4_truck" lane="E0_0" pos="400.00" period="5.00" file="e4_truck.xml" vTypes="Truck"/>
    <e1Detector id="e5" lane="E0_1" pos="0.00" period="5.00" file="e5.xml"/>
    <e1Detector id="e5_car" lane="E0_1" pos="0.00" period="5.00" file="e5_car.xml" vTypes="Car"/>
    <e1Detector id="e5_truck" lane="E0_1" pos="0.00" period="5.00" file="e5_truck.xml" vTypes="Truck"/>
    <e1Detector id="e6" lane="E0_1" pos="100.00" period="5.00" file="e6.xml"/>
    <e1Detector id="e6_car" lane="E0_1" pos="100.00" period="5.00" file="e6_car.xml" vTypes="Car"/>
    <e1Detector id="e6_truck" lane="E0_1" pos="100.00" period="5.00" file="e6_truck.xml" vTypes="Truck"/>
    <e1Detector id="e7" lane="E0_1" pos="200.00" period="5.00" file="e7.xml"/>
    <e1Detector id="e7_car" lane="E0_1" pos="200.00" period="5.00" file="e7_car.xml" vTypes="Car"/>
    <e1Detector id="e7_truck" lane="E0_1" pos="200.00" period="5.00" file="e7_truck.xml" vTypes="Truck"/>
    <e1Detector id="e8" lane="E0_1" pos="300.00" period="5.00" file="e8.xml"/>
    <e1Detector id="e8_car" lane="E0_1" pos="300.00" period="5.00" file="e8_car.xml" vTypes="Car"/>
    <e1Detector id="e8_truck" lane="E0_1" pos="300.00" period="5.00" file="e8_truck.xml" vTypes="Truck"/>
    <e1Detector id="e9" lane="E0_1" pos="400.00" period="5.00" file="e9.xml"/>
    <e1Detector id="e9_car" lane="E0_1" pos="400.00" period="5.00" file="e9_car.xml" vTypes="Car"/>
    <e1Detector id="e9_truck" lane="E0_1" pos="400.00" period="5.00" file="e9_truck.xml" vTypes="Truck"/>

</additional>
```

Chapter B
Simulation Files of SUMO for Chennai Dataset

B.1 Road Network File

```xml
<?xml version="1.0" encoding="UTF-8"?>

<net version="1.9" xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" xsi:noNamespaceSchemaLocation="http://sumo.dlr.de/xsd/net_file.xsd">

    <location netOffset="0.00,0.00" convBoundary="0.00,0.00,735.00,0.00" origBoundary="-10000000000.00,-10000000000.00,10000000000.00,10000000000.00" projParameter="!"/>

    <edge id="beg" from="gneJ0" to="gneJ1" priority="1" spreadType="roadCenter" length="735.00">
        <lane id="beg_0" index="0" speed="15.00" length="735.00" width="3.73" shape="0.00,-9.32 735.00,-9.32"/>
        <lane id="beg_1" index="1" speed="15.00" length="735.00" width="3.73" shape="0.00,-5.59 735.00,-5.59"/>
        <lane id="beg_2" index="2" speed="15.00" length="735.00" width="3.73" shape="0.00,-1.86 735.00,-1.86"/>
    </edge>

    <junction id="gneJ0" type="dead_end" x="0.00" y="0.00" incLanes="" intLanes="" shape="0.00,0.00 0.00,-11.19"/>
    <junction id="gneJ1" type="dead_end" x="735.00" y="0.00" incLanes="beg_0 beg_1 beg_2" intLanes="" shape="735.00,-11.19 735.00,0.00"/>

</net>
```

B.2 Route File

```
<routes>
    <vTypeDistribution id="mixed">
        <vType id="car" vClass="passenger" sigma="0.5" maxSpeed="8.71" accel="4.436" decel="4.371" speedDev="0.1" latAlignment="arbitrary" probability="0.266"/>
        <vType id="moped" vClass="motorcycle" sigma="0.5" maxSpeed="8.89" accel="4.734" decel="4.659"  speedDev="0.1" latAlignment="arbitrary" probability="0.564"/>
        <vType id="rickshaw" sigma="0.5" length="2.62" width="1.2" height="1.7" maxSpeed="7.44" accel="4.501" decel="4.340" latAlignment="arbitrary" probability="0.122" color="0,1,1" />
        <vType id="bus" vClass="bus" sigma="0.5" maxSpeed="7.9" accel="3.981" decel="4.208" latAlignment="arbitrary" probability="0.048" color="1,0,0" />
    </vTypeDistribution>
    <route id="r0" edges="beg"/>
    <flow id="mixed" begin="0" end="5400" vehsPerHour="6010" route="r0" type="mixed" departLane="random" departPosLat="random"/>
</routes>
```

B.3 Configuration Files

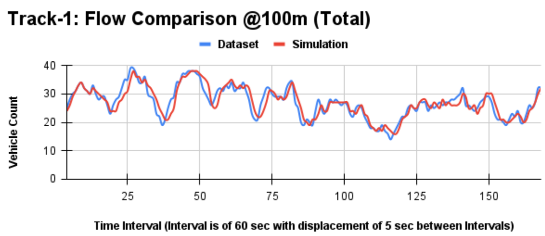
```
<?xml version="1.0" encoding="UTF-8"?>
<configuration xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" xsi:noNamespaceSchemaLocation="http://sumo.dlr.de/xsd/sumoConfiguration.xsd">
    <input>
        <net-file value="net.net.xml"/>
        <route-files value="input_routes.rou.xml"/>
        <additional-files value="additional-2.xml"/>
    </input>
    <output>
        <write-license value="true"/>
        <fcd-output value="fcd-2.xml"/>
        <fcd-output.acceleration value="true"/>
    </output>
    <processing>
        <lateral-resolution value="0.31"/>
    </processing>
</configuration>
```

B.4 Additional Files

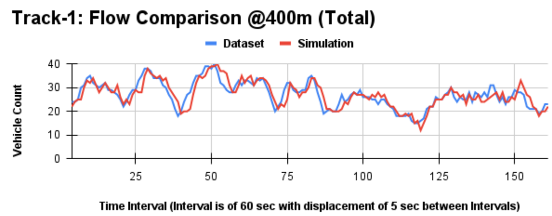
```xml
<?xml version="1.0" encoding="UTF-8"?>
<!-- generated on 2023-07-18 14:23:42 by Eclipse SUMO netedit
    Version 1.14.1-->

<additional xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
    xsi:noNamespaceSchemaLocation="http://sumo.dlr.de/xsd/
    additional_file.xsd">
     <!-- Detectors -->
     <e1Detector id="e1_0" lane="beg_0" pos="370.00" period="1800.00"
     file="d1.xml"/>
     <e1Detector id="e1_1" lane="beg_1" pos="370.00" period="1800.00"
     file="d2.xml"/>
     <e1Detector id="e1_10" lane="beg_1" pos="370.00" period="1800.00
    " file="d2_r.xml" vTypes="rickshaw"/>
     <e1Detector id="e1_11" lane="beg_2" pos="370.00" period="1800.00
    " file="d3_r.xml" vTypes="rickshaw"/>
     <e1Detector id="e1_12" lane="beg_0" pos="370.00" period="1800.00
    " file="d1_t.xml" vTypes="bus"/>
     <e1Detector id="e1_13" lane="beg_1" pos="370.00" period="1800.00
    " file="d2_t.xml" vTypes="bus"/>
     <e1Detector id="e1_14" lane="beg_2" pos="370.00" period="1800.00
    " file="d3_t.xml" vTypes="bus"/>
     <e1Detector id="e1_2" lane="beg_2" pos="370.00" period="1800.00"
     file="d3.xml"/>
     <e1Detector id="e1_3" lane="beg_0" pos="370.00" period="1800.00"
     file="d1_c.xml" vTypes="car"/>
     <e1Detector id="e1_4" lane="beg_1" pos="370.00" period="1800.00"
     file="d2_c.xml" vTypes="car"/>
     <e1Detector id="e1_5" lane="beg_2" pos="370.00" period="1800.00"
     file="d3_c.xml" vTypes="car"/>
     <e1Detector id="e1_6" lane="beg_0" pos="370.00" period="1800.00"
     file="d1_m.xml" vTypes="moped"/>
     <e1Detector id="e1_7" lane="beg_1" pos="370.00" period="1800.00"
     file="d2_m.xml" vTypes="moped"/>
     <e1Detector id="e1_8" lane="beg_2" pos="370.00" period="1800.00"
     file="d3_m.xml" vTypes="moped"/>
     <e1Detector id="e1_9" lane="beg_0" pos="370.00" period="1800.00"
     file="d1_r.xml" vTypes="rickshaw"/>

</additional>
```

CHAPTER C

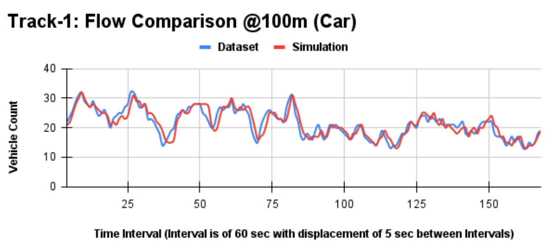
Track-1 (Result Analysis)



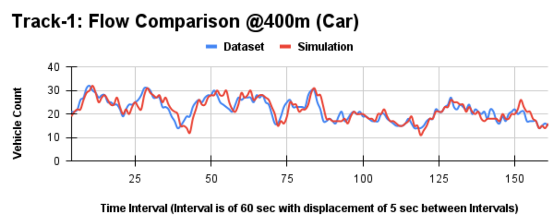
(a) RMSE of Total Vehicles'Flow at 100m: 8.17 with Mean Error of -0.06



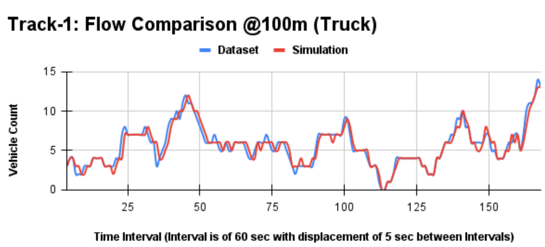
(b) RMSE of Total Vehicles'Flow at 400m: 10.33 with Mean Error of -0.06



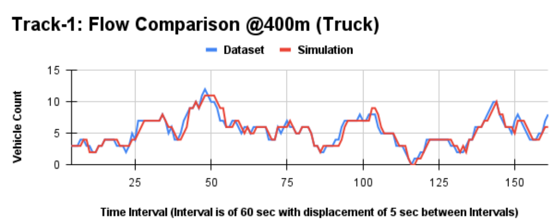
(c) RMSE of Total Cars'Flow at 100m: 9.01 with Mean Error of -0.02



(d) RMSE of Total Cars'Flow at 400m: 11.10 with Mean Error of -0.02



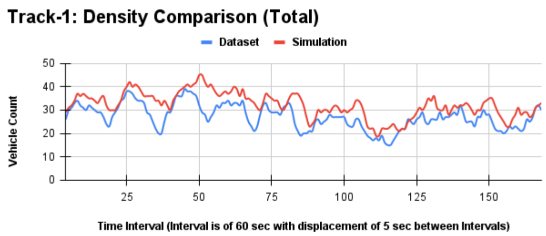
(e) RMSE of Total Trucks'Flow at 100m: 12.89 with Mean Error of -0.04



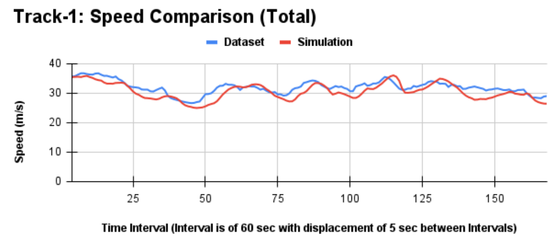
(f) RMSE of Trucks'Flow at 400m: 14.16 with Mean Error of -0.04

Figure C.1: Flow Results of Track-1

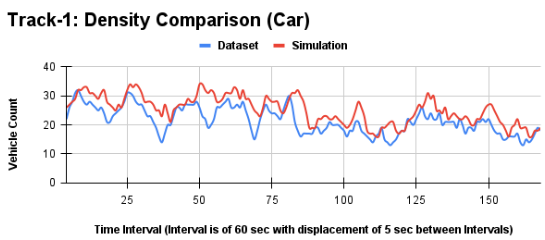
Upon examining the graphs depicted in figure C.1, it becomes apparent that the traffic flow at 100 meters and 400 meters closely aligns with the simulation model. This observation indicates that the simulation model accurately captures the dynamics of traffic flow in the specified scenarios, resulting in accurate results.



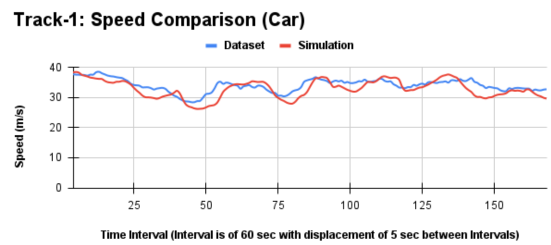
(a) RMSE of Total Density: 23.18 with Mean Error of 5.07



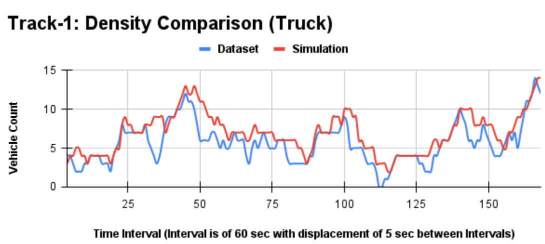
(b) RMSE of Total Speed: 6.44 with Mean Error of -1.39



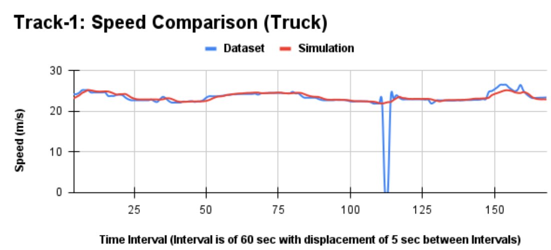
(c) RMSE of Car Density: 22.77 with Mean Error of 3.76



(d) RMSE of Car Speed: 6.47 with Mean Error of -1.16



(e) RMSE of Truck Density: 34.43 with Mean Error of 1.31



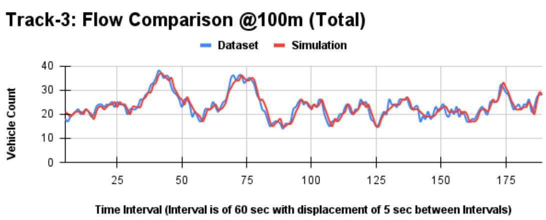
(f) RMSE of Truck Speed: 10.72 with Mean Error of 0.29

Figure C.2: Speed and Density Results of Track-1

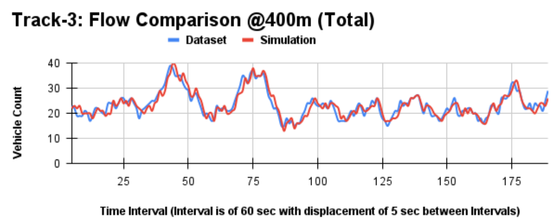
Figure C.2 reveals that traffic density does not align well with the dataset, exhibiting a notable level of error, especially for trucks. However, traffic speed shows a close match to the dataset, indicating that the simulation model effectively captures the dynamics of traffic speed. Nevertheless, there are challenges in accurately representing traffic density, particularly for heavy vehicles. Further investigation and SUMO tuning of SUMO parameters is needed to enhance the accuracy of traffic density predictions in the simulation model.

Chapter D

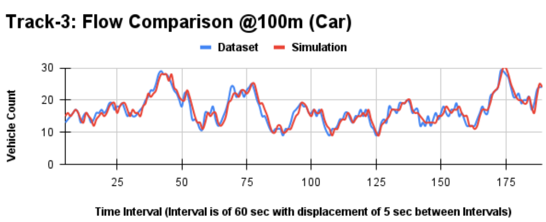
Track-3: Result Analysis



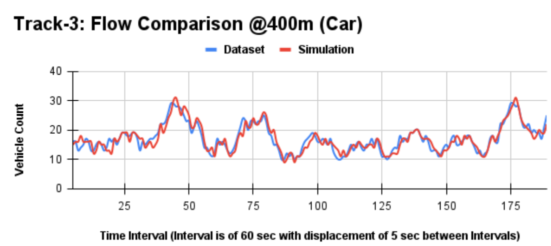
(a) RMSE of Total Vehicles'Flow at 100m: 7.17 with Mean Error of -0.02



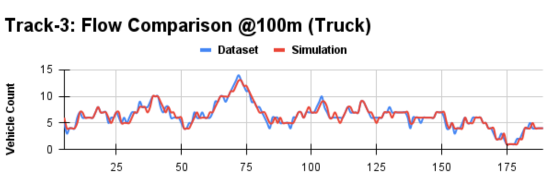
(b) RMSE of Total Vehicles'Flow at 400m: 8.29 with Mean Error of -0.01



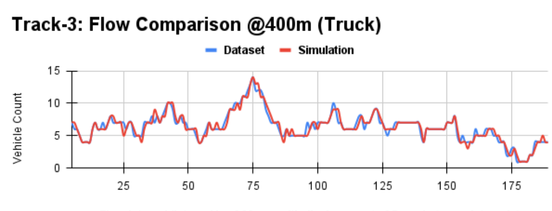
(c) RMSE of Total Cars'Flow at 100m: 8.81 with Mean Error of -0.02



(d) RMSE of Total Cars'Flow at 400m: 10.14 with Mean Error of -0.01



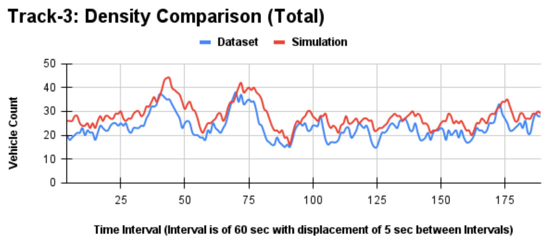
(e) RMSE of Total Trucks'Flow at 100m: 9.68 with Mean Error of -0.01



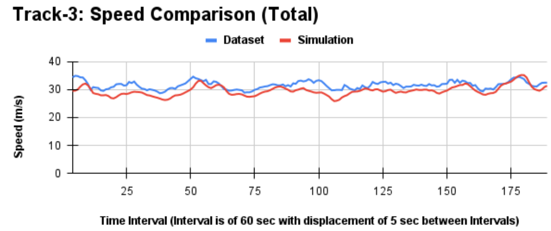
(f) RMSE of Trucks'Flow at 400m: 9.46 with Mean Error of -0.01

Figure D.1: Flow Results of Track-3

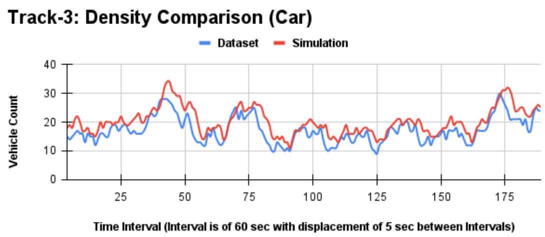
After analyzing the graphs in Figure D.1, it is clear that the traffic flow at both 100 meters and 400 meters closely matches the simulation model. This indicates that the simulation model very well captures the dynamics of traffic flow in the given scenarios, resulting in accurate results.



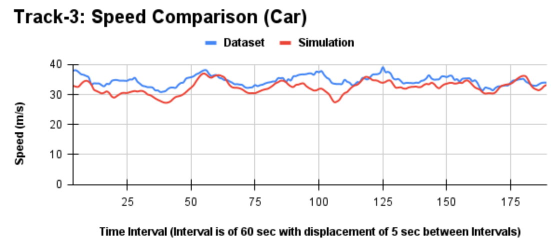
(a) RMSE of Total Density: 23.37 with Mean Error of 4.68



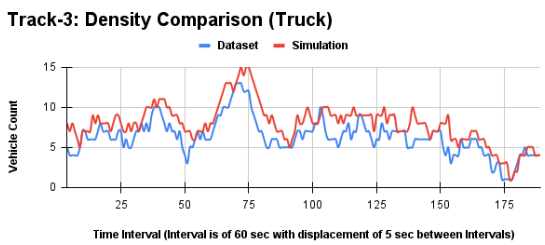
(b) RMSE of Total Speed: 7.53 with Mean Error of -2.02



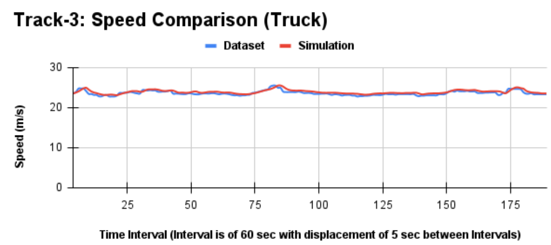
(c) RMSE of Car Density: 22.62 with Mean Error of 3.04



(d) RMSE of Car Speed: 8.09 with Mean Error of -2.23



(e) RMSE of Truck Density: 32.40 with Mean Error of 1.63



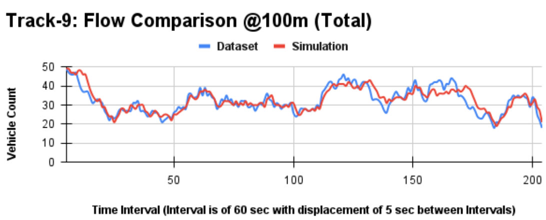
(f) RMSE of Truck Speed: 1.78 with Mean Error of 0.30

Figure D.2: Speed and Density Results of Track-3

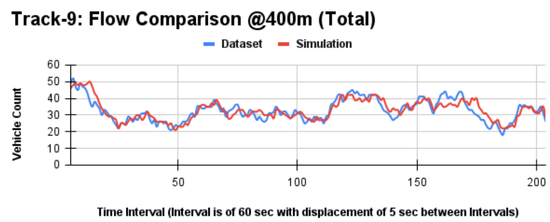
The analysis of Figure D.2 reveals that traffic density shows a weak correlation with the dataset and has a considerable level of error, especially for trucks. Nevertheless, traffic speed exhibits a close resemblance to the dataset. These findings indicate that the simulation model effectively captures traffic speed dynamics but encounters difficulties in accurately representing traffic density, particularly for heavy vehicles. Further investigation and tuning of SUMO parameters is required to improve the accuracy of traffic density predictions.

CHAPTER E

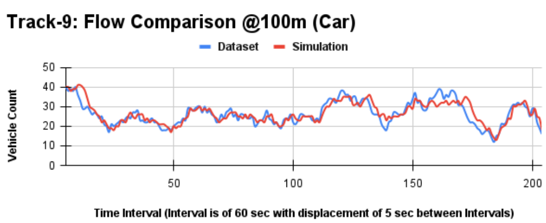
Track-9: Result Analysis



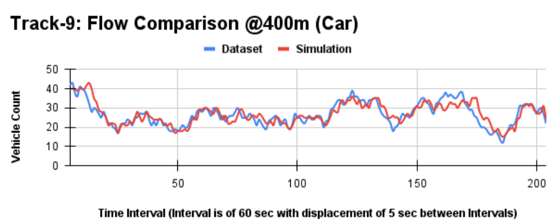
(a) RMSE of Total Vehicles'Flow at 100m: 9.65 with Mean Error of 0.28



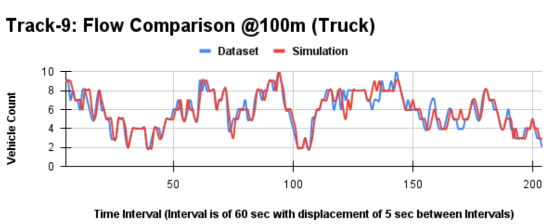
(b) RMSE of Total Vehicles'Flow at 400m: 10.42 with Mean Error of 0.22



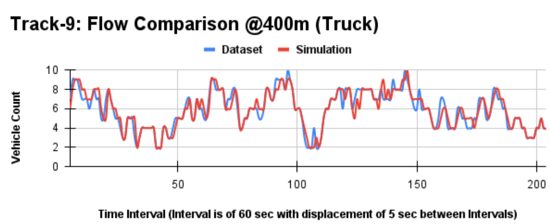
(c) RMSE of Total Cars'Flow at 100m: 11.36 with Mean Error of 0.24



(d) RMSE of Total Cars'Flow at 400m: 12.03 with Mean Error of 0.19



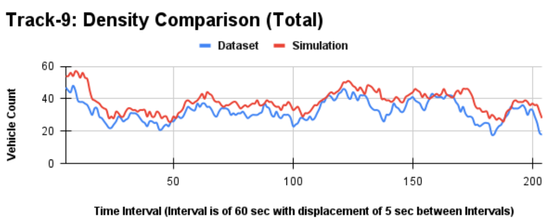
(e) RMSE of Total Trucks'Flow at 100m: 13.65 with Mean Error of 0.04



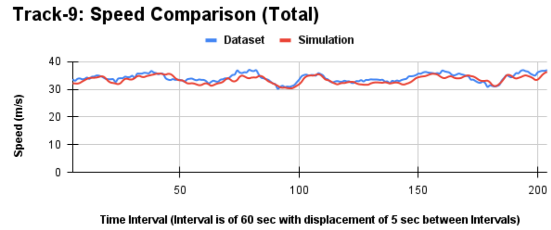
(f) RMSE of Trucks'Flow at 400m: 11.37 with Mean Error of 0.03

Figure E.1: Flow Results of Track-9

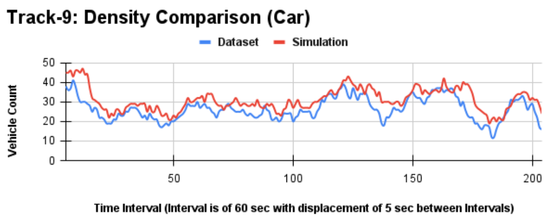
Upon reviewing the graphs in figure E.1, it is clear that the traffic flow at both 100 meters and 400 meters closely matches the simulation model. This indicates that the simulation effectively captures the traffic flow dynamics, leading to accurate results.



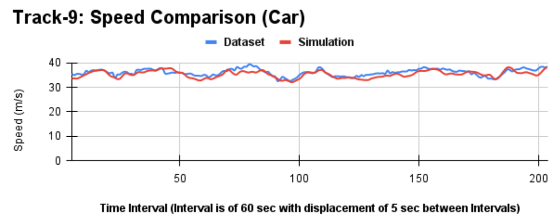
(a) RMSE of Total Density: 22.36 with Mean Error of 6.04



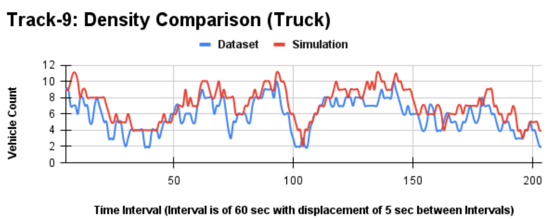
(b) RMSE of Total Speed: 3.55 with Mean Error of -0.75



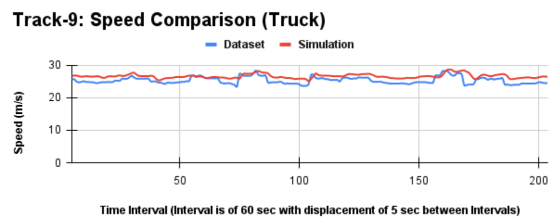
(c) RMSE of Car Density: 22.58 with Mean Error of 4.68



(d) RMSE of Car Speed: 3.47 with Mean Error of 1.37



(e) RMSE of Truck Density: 31.66 with Mean Error of -0.76



(f) RMSE of Truck Speed: 6.03 with Mean Error of 1.30

Figure E.2: Speed and Density Results of Track-9

The analysis of figure E.2 indicates that traffic density does not align well with the dataset, resulting in considerable errors, particularly for trucks. Nonetheless, traffic speed shows a close resemblance to the dataset, implying that the simulation model effectively captures speed dynamics. However, accurately representing traffic density, especially for heavy vehicles, poses challenges. Further investigation and tuning of SUMO parameters is required to refine the accuracy of traffic density predictions.