



Title

"Machine Learning-Based Traffic Congestion Classification
for Urban Road Networks"

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Abstract

Urban traffic congestion undermines mobility, energy efficiency, and safety. This thesis develops a machine-learning framework to classify traffic states—Normal, Heavy Traffic, and Very Heavy Traffic—using historical vehicle-count and temporal features from urban road networks. The pipeline includes data cleaning, exploratory data analysis, and feature engineering to derive time-period indicators and day-level attributes. Two representative classifiers are built and compared: Random Forest and L2-regularized Logistic Regression. Models are evaluated using accuracy, precision, recall, and F1-score, and their behavior is interpreted through feature-importance analyses. Results show that Random Forest attains very high training performance but exhibits overfitting, whereas the L2-regularized logistic model generalizes more reliably to unseen data. The analysis identifies time-of-day context and vehicle-type counts as the most discriminative predictors of congestion level. The study contributes a reproducible, low-cost, data-driven approach for augmenting Intelligent Transportation Systems (ITS) in settings where extensive sensing infrastructure is impractical, and offers practical guidance on model choice, feature design, and evaluation for deployment-oriented congestion classification.

Table of Contents

List of Abbreviations	vi
List of Figures.....	vii
List of Tables	vii
Chapter 1: Introcudion	8
1.1 Problem Definition	8
1.2 Thesis Objectives	8
1.3 Thesis Contribution	9
1.4 Thesis Organization.....	9
Chapter 2: Overview.....	10
2.1 Introduction	11
2.2 Educational Data Mining	12
2.3 Applications of Educational Data Mining	17
Chapter 3: Related Work	18
3.1 Introduction	19
3.2 History	21
Chapter 4: Proposed Approach	22
4.1 Introduction	23
Chapter 5: Experimental Results and Discussion	24
Chapter 6: Conclusion and Future Work	29
7.1 Important Features	29
7.3 Future Work	29
References	31

List of Abbreviations

ML: Machine Learning
RF: Random Forest
LR: Logistic Regression
L2: L2 Regularization
EDA: Exploratory Data Analysis
ITS: Intelligent Transportation Systems
CNN: Convolutional Neural Networks
LSTM: Long Short-Term Memory
DBN: Deep Belief Network
GNN: Graph Neural Networks

List of Figures

Figure1:descriptive statistics of dataset

Figure2: chart of car count vs hour.

Figure3: chart of bus count vs hour.

Figure4: chart of bike count vs hour.

Figure5: chart of truck count vs hour.

Figure6: chart of total vehicles vs hour.

Figure7: Average Vehicle Count by Day of the Week.

Figure8: Boxplot of Vehicle Count Distributions by Type.

Figure9: distribution of classes vs total.

Figure10: Confusion matrix of RF.

Figure11: feature importance of model1.

Figure12: Confusion matrix of l2 of logistic regression.

Figure13:feature importance of model2.

List of Tables

Table1: Data Set Description

Table2: Performance of models

Chapter 1 Introduction

1.1 Problem Definition

The rapid increase in the number of vehicles has led to frequent traffic jam in urban areas. Managing traffic efficiently is critical to reducing delays, reducing fuel consumption, and improving safety. Traditional traffic monitoring systems rely on manual monitoring or expensive sensor infrastructure, which can be less scalable. This project aims to develop a machine learning-based traffic classification system that predicts whether traffic conditions are normal, heavy, or extremely heavy, based on historical traffic data.

1.2 Thesis Objectives

1. Conduct data preprocessing and electronic data analysis to understand traffic patterns.
2. Implement and compare Random Forest and Logistic Regression with L2 Regularization models.
3. Using matrix to evaluate models: accuracy, precision, recall, and F1 score.
4. Recognize the most important features that influence traffic forecasting.

1.3 Thesis Contribution

- Developing the pipeline for traffic classification using machine learning.
- Comparative study of RF and LR-L2 models for traffic prediction.

- Feature importance analysis to identify the key factors that influence traffic flow.
- Recommendations for integrating the model into real-time traffic management systems.

1.4 Thesis Organization

Chapter1: introduces the research problem, objectives, and contributions.
Chapter2: presents an overview of traffic prediction concepts and related work.
Chapter3: discusses previous studies on traffic status prediction.
Chapter4: describes the proposed machine learning approach.
Chapter5: presents experimental results and performance analysis.
Chapter6: concludes the thesis and suggests future work.

Chapter 2 Overview

2.1 introduction

Traffic status prediction is an essential element in Intelligent Transportation Systems (ITS), enabling proactive measures to alleviate congestion.

From Kaggle using the dataset in file .csv contain 14 features(day of week,time,date, Bike count, Bus Count, Car count,Truck Count, Total, Hour, Minute,, time_period, day_of_week, Time_of_month)and label column contain four classes(heavy,high,low,normal).

This dataset constitutes an integral part of transportation planning, traffic congestion management, and traffic flow studies this system provides insights into vehicle demand, highlights zones characterized by elevated traffic density, and informs infrastructure enhancement initiatives. By enabling specific actions such as improved traffic signals and lane redesign, the system enhances the efficiency of roadway usage. Researchers can analyze traffic trends by hour, day, or specific dates and analyze the relationships with external factors. It also facilitates studies on vehicle interactions and overall traffic behavior. Urban planners may employ it to evaluate traffic conditions impact of zoning and infrastructure projects. Ultimately, the dataset provides decision-makers with the tools to make informed, data-driven choices that improve mobility, enhance efficiency, and promote sustainable urban development. [1]

2.2 Traffic Data Mining

Data mining is the process mining patterns and constructing relevant knowledge. In our project, we apply data mining techniques to the traffic domain to classify, analyze, and predict traffic conditions (heavy, high, and normal, low). Comprehending traffic flow dynamics (an important feature for which we employed the numerical value and timing of vehicles) and analyzing their data enables us to generate reliable predictions that support transportation planning.

	Date	CarCount	BikeCount	BusCount	TruckCount	Total	Hour
count	2976.000000	2976.000000	2976.000000	2976.000000	2976.000000	2976.000000	2976.000000
mean	16.000000	68.696573	14.917339	15.279570	15.324933	114.218414	11.500000
std	8.945775	45.850693	12.847518	14.341986	10.603833	60.190627	6.92335
min	1.000000	6.000000	0.000000	0.000000	0.000000	21.000000	0.000000
25%	8.000000	19.000000	5.000000	1.000000	6.000000	55.000000	5.750000
50%	16.000000	64.000000	12.000000	12.000000	14.000000	109.000000	11.500000
75%	24.000000	107.000000	22.000000	25.000000	23.000000	164.000000	17.250000
max	31.000000	180.000000	70.000000	50.000000	40.000000	279.000000	23.000000

minute	day_of_month
2976.000000	2976.000000
22.500000	16.000000
16.773328	8.945775
0.000000	1.000000
11.250000	8.000000
22.500000	16.000000
33.750000	24.000000
45.000000	31.000000

figure1: descriptive statistics of dataset in kaggle notebook [2]

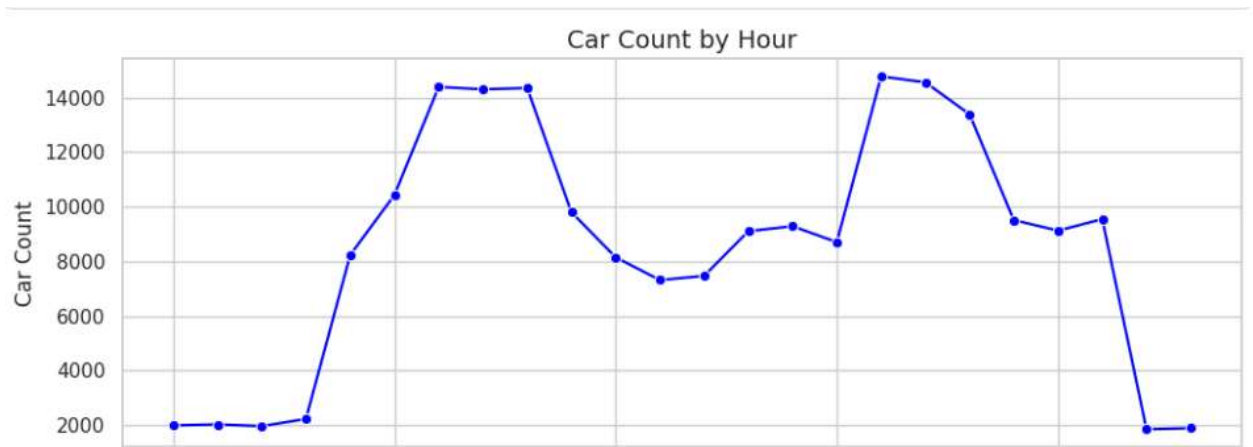


Figure2:chart of car count vs hour [2]

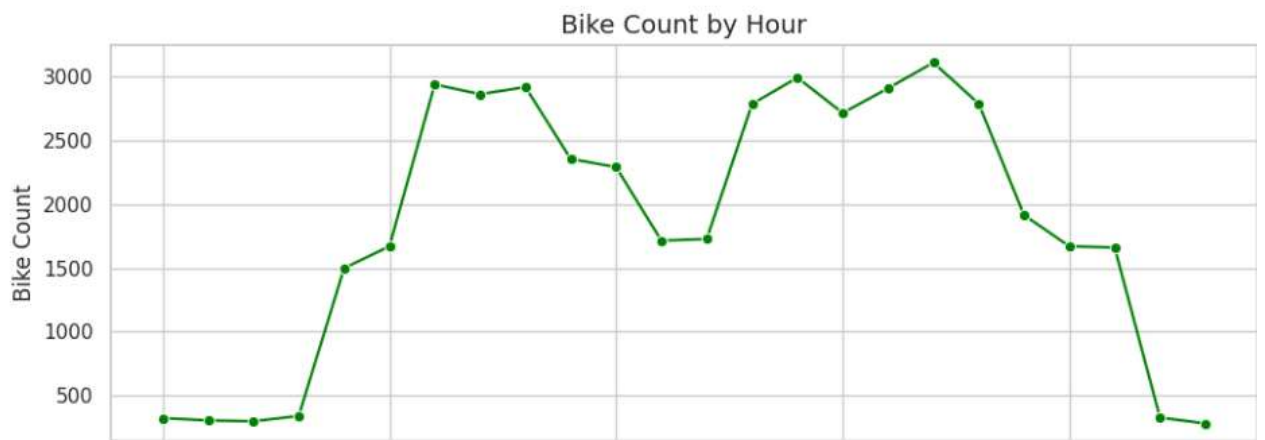


Figure3: chart of Bike count vs hour[2]

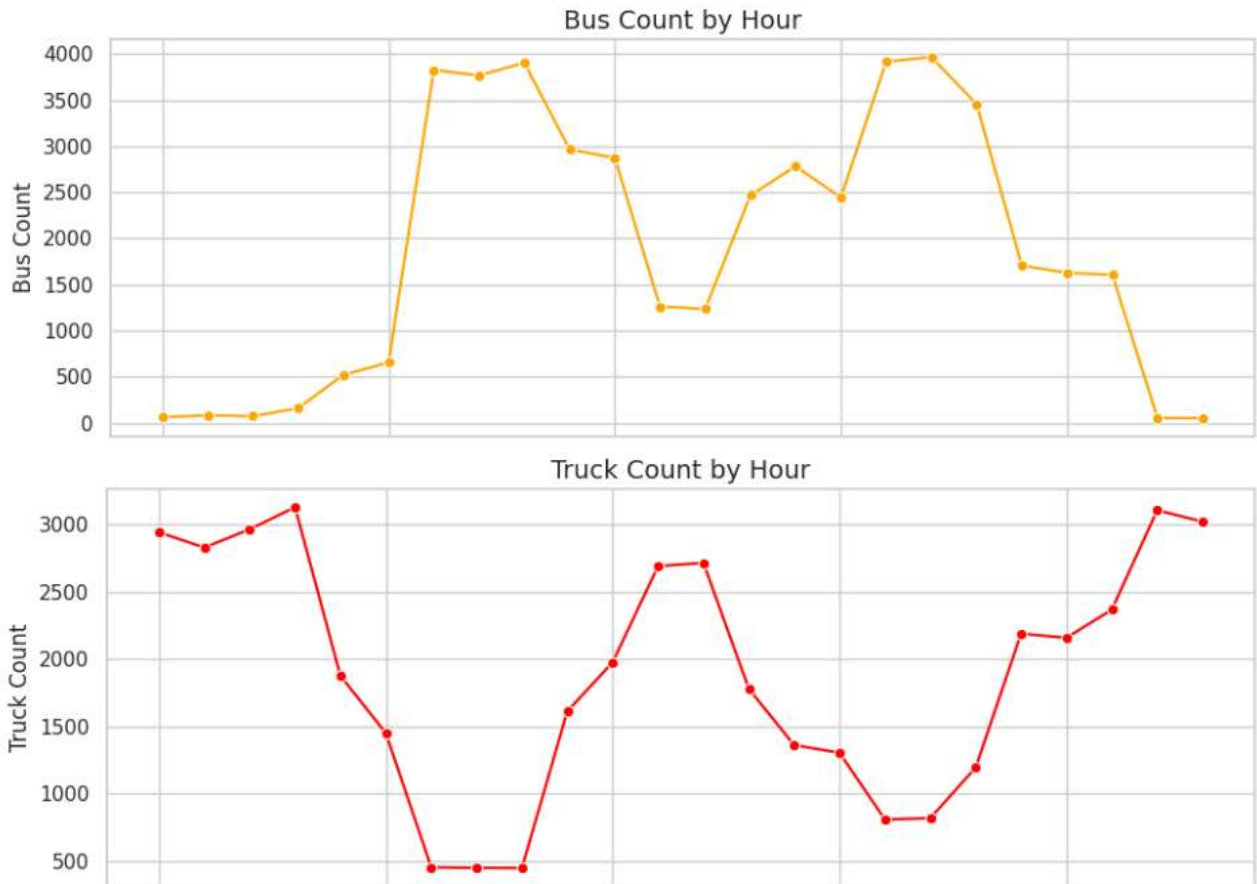


Figure4: chart of Bus vs Hour

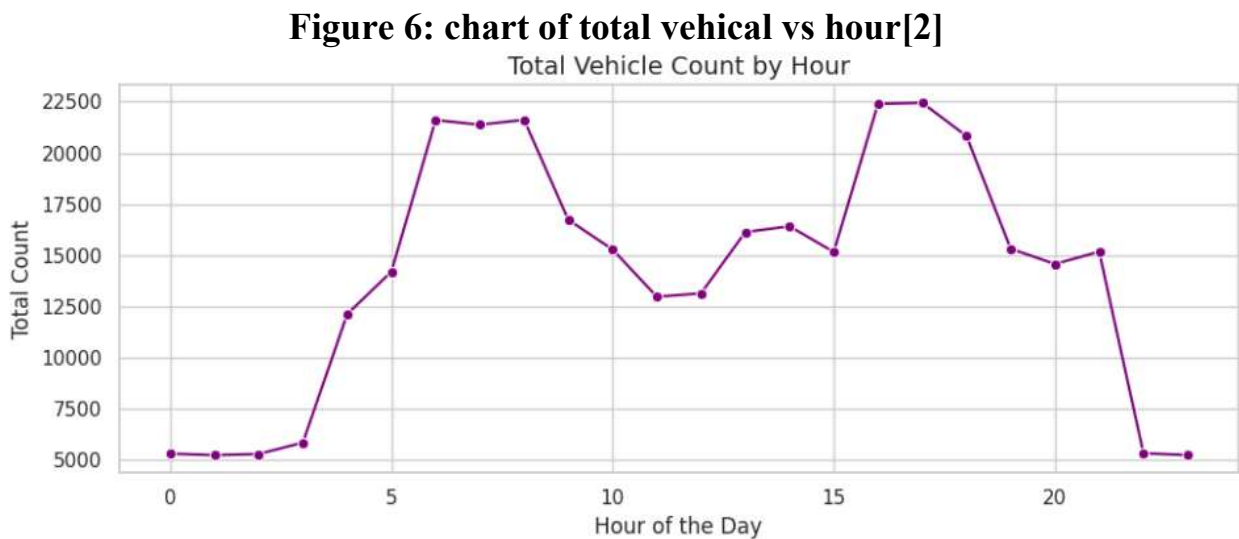


Figure5: chart of truck count vs hour [2]

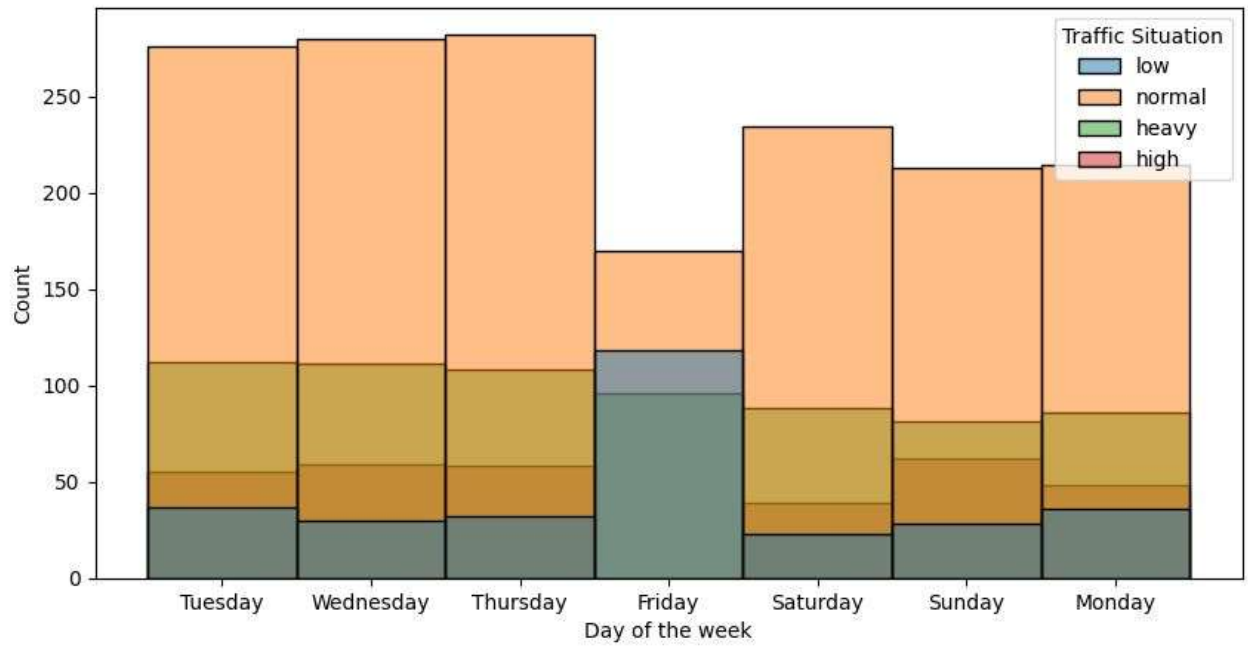


Figure7:chart of traffic situation during week days[2]

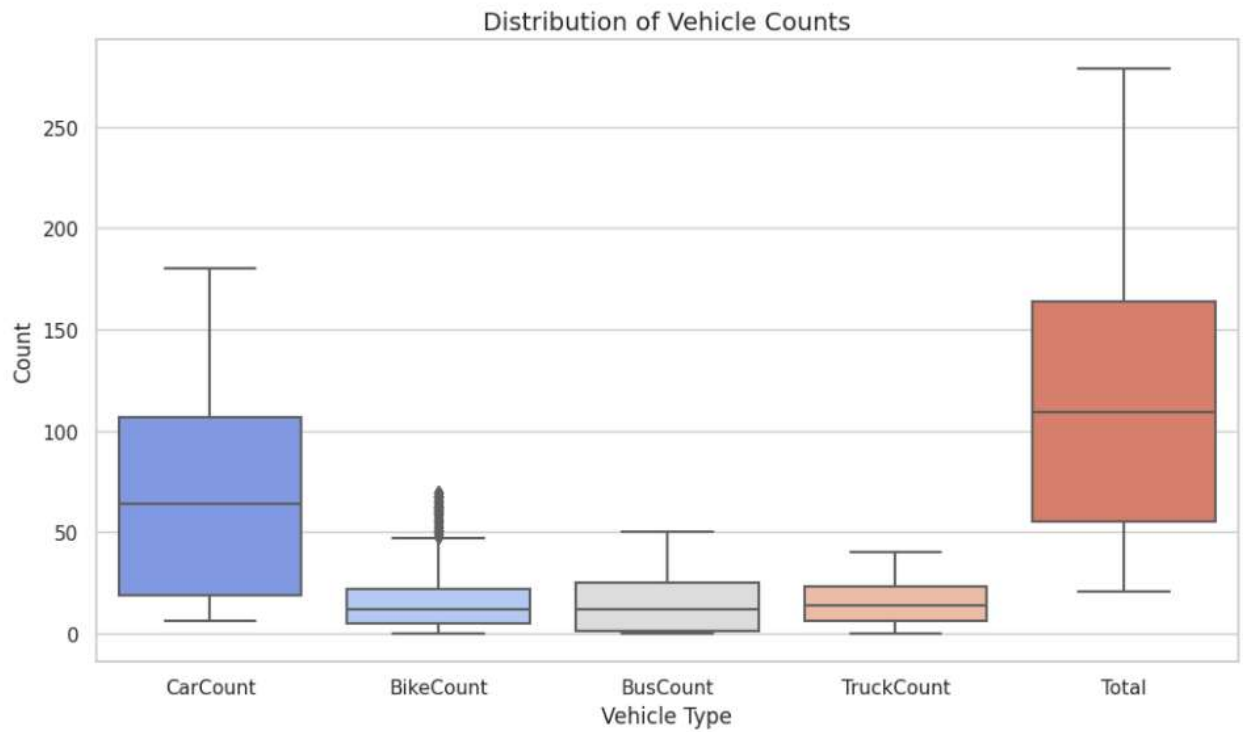


Figure8:check outlier of vehical types counts[2]

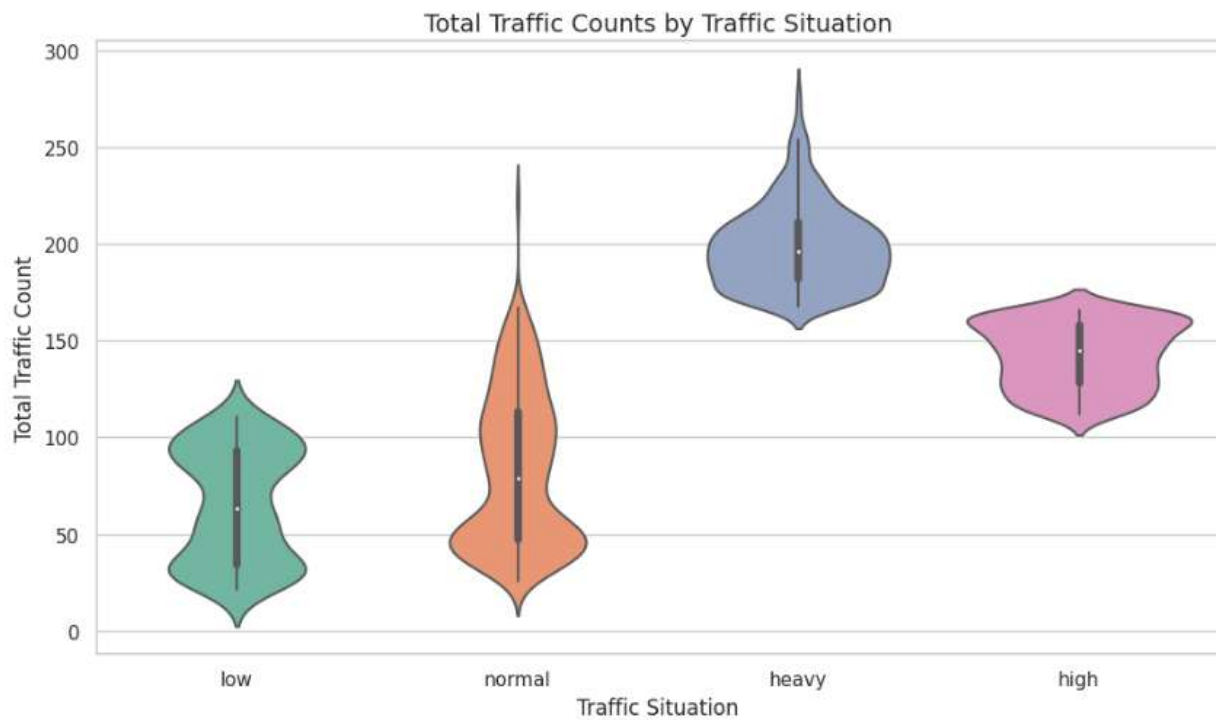


figure9: number of each class (heavy,high,normal,low)[2]

Chapter 3 Related Work

3.1 Introduction:

Research on traffic congestion classification has gained momentum as part of the growing field of Intelligent Transportation Systems (ITS). Earlier monitoring approaches depended mainly on manual checks and costly infrastructure, which made them difficult to scale. With the development of machine learning, however, sensor-based methods have started to play a central role in congestion analysis and anomaly detection. In this section, I review several key studies, highlighting their contributions and limitations, and point out the gaps that inform the direction of this thesis.

Traffic Flow State Classification via Smartphone Sensors (Tu et al., 2017)

Tu and colleagues explored the use of data from smartphone sensors—accelerometers, gyroscopes, and GPS—to identify traffic states through a Deep Belief Network (DBN). Their approach performed better than traditional techniques in terms of accuracy and efficiency. Even so, the dataset was limited both in time span and location, which makes it uncertain whether the findings can be generalized to other contexts.

Detecting and Predicting Traffic Congestion Anomalies (Mihaita et al., 2020)

In a different setting, Mihaita et al. proposed a CNN–LSTM model trained on more than 36 million sensor readings from Sydney’s motorway loops. By applying anomaly adjustment, their system was able to capture spatial and temporal congestion patterns more effectively than baseline models. The results were strong, but the focus on only one metropolitan area limits how far the findings can be extended.

A New Approach to Congestion and Anomaly Detection (Ben Slimane & Ben Ammar, 2024)

Ben Slimane and Ben Ammar introduced a deep learning framework for real-time congestion and anomaly detection in urban networks. Their architecture, combining CNN and LSTM, showed notable gains in accuracy, precision, recall, and efficiency compared to established methods. Still, the study offered little

detail about how the dataset was collected or what areas it covered, which poses challenges for reproducibility.

Adaptive Traffic Prediction with Edge-Impulse TinyML (Tolani et al., 2025)

More recently, Tolani and colleagues used proximity sensors installed at signalized intersections together with a TinyML model on the Edge-Impulse platform. The system forecasted traffic density and vehicle arrival times, then adjusted signal timings dynamically. Compared with fixed-time systems, it reduced congestion effectively. That said, the approach was tested only at selected intersections, leaving questions about whether it could scale to larger and more complex road networks.

Study	Authors	Year	Research Design	Key Findings / Results	Methodology	Limitations
Traffic Flow State Classification via Smartphone Sensors	Tu et al.	2017	Experimental study using DBN	Outperformed traditional classification methods in accuracy and efficiency	Deep Belief Network on smartphone sensor data (accelerometer, gyroscope, GPS; 747,856 samples / 5 days)	Short-term dataset; limited generalizability
Traffic Congestion Anomaly Detection and Prediction	Mihaita et al.	2020	Hybrid CNN-LSTM framework	Consistently outperformed traditional models; anomaly adjustment improved predictions	Hybrid CNN-LSTM applied to 36.34 million motorway loop readings from Sydney	Single-city dataset; focused on highways only
A Novel Approach for Congestion and Anomaly Detection	Ben Slimane & Ben Ammar	2024	Hybrid deep learning framework	Higher accuracy, precision, recall, and efficiency than benchmarks	CNN-LSTM with real-time feature extraction and urban dataset	Limited dataset transparency; reproducibility concerns
Edge-Impulse TinyML Adaptive Traffic Prediction	Tolani et al.	2025	Applied Edge ML with proximity sensors to predict traffic density and vehicle arrival times.	Congestion is reduced by dynamically adjusting signal timings in real time.	Proximity sensors + Edge-Impulse ML model for adaptive traffic signal control.	Limited to specific junctions; scalability across larger road networks not yet demonstrated.

3.2 History:

Early research on traffic analysis leaned on statistical and regression models to describe flow patterns. Those tools were useful to a point, but they struggled with the inherently dynamic and nonlinear behavior of urban traffic. As larger sensor datasets became available and machine learning matured, the field moved toward models that can capture richer structure—most notably CNNs, LSTMs, and hybrid designs. In practice, these approaches improved congestion-level prediction, anomaly detection, and decisions that must be taken in real time. A concise summary of representative studies appears in the table that follows.

Chapter 4 Proposed Approach

4.1 Introduction:

The approach uses the traffic prediction dataset from Kaggle, applying two classification models: random forest (ensemble learning) and logistic regression with L2 regularization.

Pipeline steps:

1-import libraries (numpy: mathematical library, pandas: read file of csv data and preprocess, matplotlib: visualization dataset and seaborn correlations of columns)

2-read dataset: use function of `read_csv ()` in library of pandas

3-Discover the dataset (use the `shape` method to display rows numbers and columns, use the `unique ()` accessor method for date columns to make all dates unique, use the `info ()` method to inform the data types) null values in dataset and use finally `drop_duplicates ()` to check duplicate values.

4- Exploratory data analysis (EDA):

Use various charts:

The first graph (line graph) shows the relationship between the number of vehicles per hour, the breakdown by type, and the total, indicating that the number of cars is the highest.

Second chart :(barplot) show relationship between Average Vehicle Count by Day of the Week indicate the most days heavy traffic Tuesday, Wednesday.

Third chart :(boxplot) check outlier in vehicle type(car, bus, truck, bike, total vehicle) indicate no outlier.

Fourth chart :(pie) Average Contribution of Vehicle Types to Total Traffic indicate car count most vehicles in total.

Fifth chart :(Violin Plot) show relationship between Total Traffic Counts by Traffic Situation indicate normal traffic states most.

5-feature engineering:

Convert date to details day,month and time_period.

6-build first model Random Forest:

Frist converting columns by label encoder to numeric datatypes ['hour', 'minute', 'CarCount', 'BikeCount', 'BusCount', 'TruckCount', 'day_of_week', 'day_of_month', 'time_period']] then build model RF with hyperparameter n_estimators=100, random_state=42 and train model with fit() function and test with function predict() found accuracy about 100% this indicate overfitting we solve it in second model. finally visualize most important feature model depend on it is car count.

7-build second model Logistic Regression:

Start with convert this columns by label encoder to numeric datatypes ['hour', 'minute', 'Car Count', 'Bike Count', 'Bus Count', 'Truck Count', 'day_of_week', 'day_of_month', 'time_period']

then build model LR with hyperparameter penalty='l2', # Use L2 regularization

C=1.0, # Inverse of regularization strength

solver='lbfgs', # Optimization algorithm

max_iter=1000, # Maximum number of iterations for convergence

random_state=42

And train model with fit() function and test with function predict() found accuracy about 89% this indicate we solve problem of overfitting . finally visualize most important feature model depend on it is time_period.

Chapter 5

Experimental Results and Discussion

Below are the models performance results including confusion matrices and feature importance chart of two models (random forest, l2 of logistic regression)

First model: random forest

```
array([[123,  3,  0,  1],  
       [ 5, 51,  0,  7],  
       [ 0,  0, 64,  2],  
       [ 8,  3,  1, 328]])
```

Training Accuracy: 1.00

Test Accuracy: 0.95

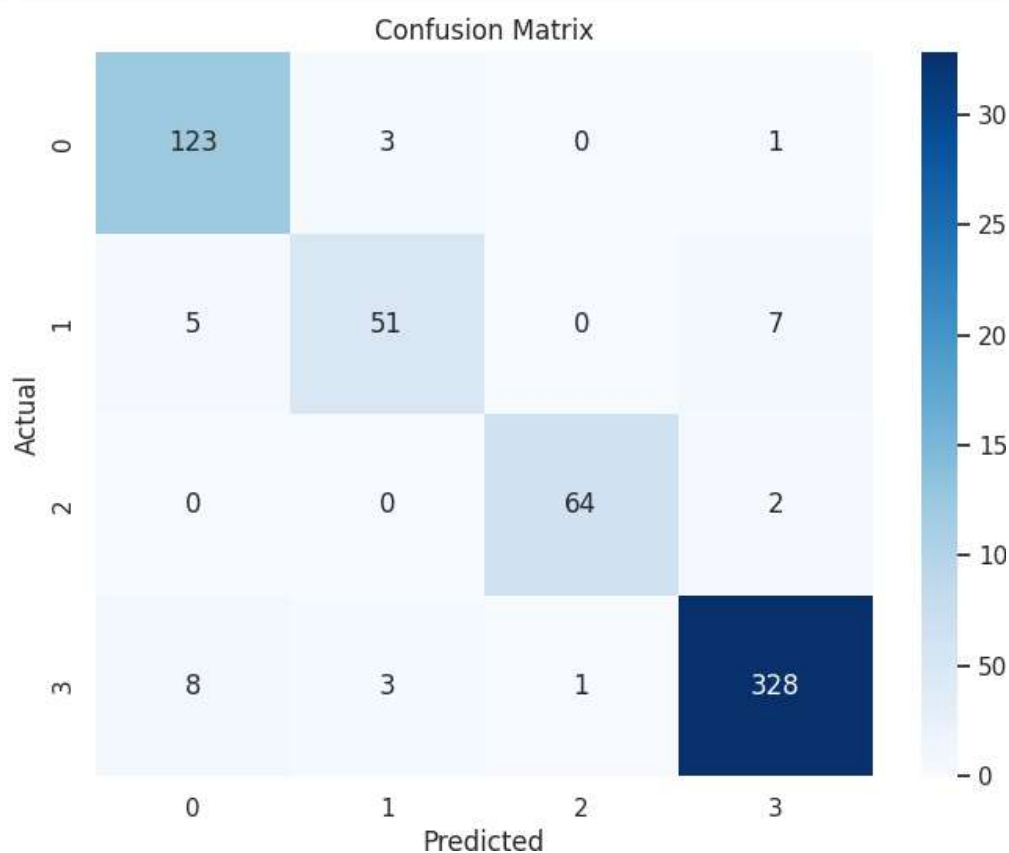


Figure12: Confusion matrix of RF.[2]

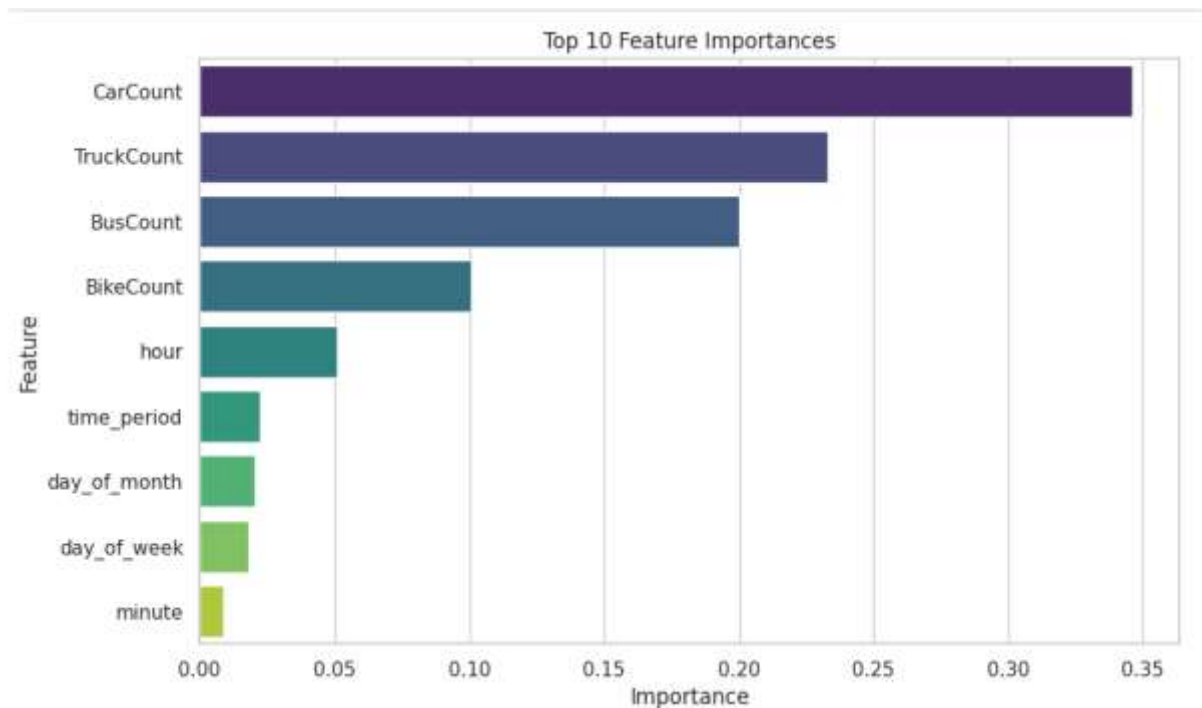


Figure13: feature importance of model1 [2]

The model shows the accuracy training of 1.00 and the accuracy testing of 0.95, indicating potential overfitting. This occurs when the model memorizes the training data, including noise, resulting in high training accuracy but lower generalization to unseen data. To mitigate overfitting, regularization techniques are essential, as they penalize large parameters and encourage the construction of simpler models, which improves generalization and enhances model robustness.

Second model: l2 of logistic regression

```
array([[124,  3,  0,  0],  
       [ 13, 38,  0, 12],  
       [  0,  0, 49, 17],  
       [ 11,  4,  9, 316]])
```

	precision	recall	f1-score	support
heavy	0.84	0.98	0.90	127
high	0.84	0.60	0.70	63
low	0.84	0.74	0.79	66
normal	0.92	0.93	0.92	340
accuracy			0.88	596
macro avg	0.86	0.81	0.83	596
weighted avg	0.88	0.88	0.88	596

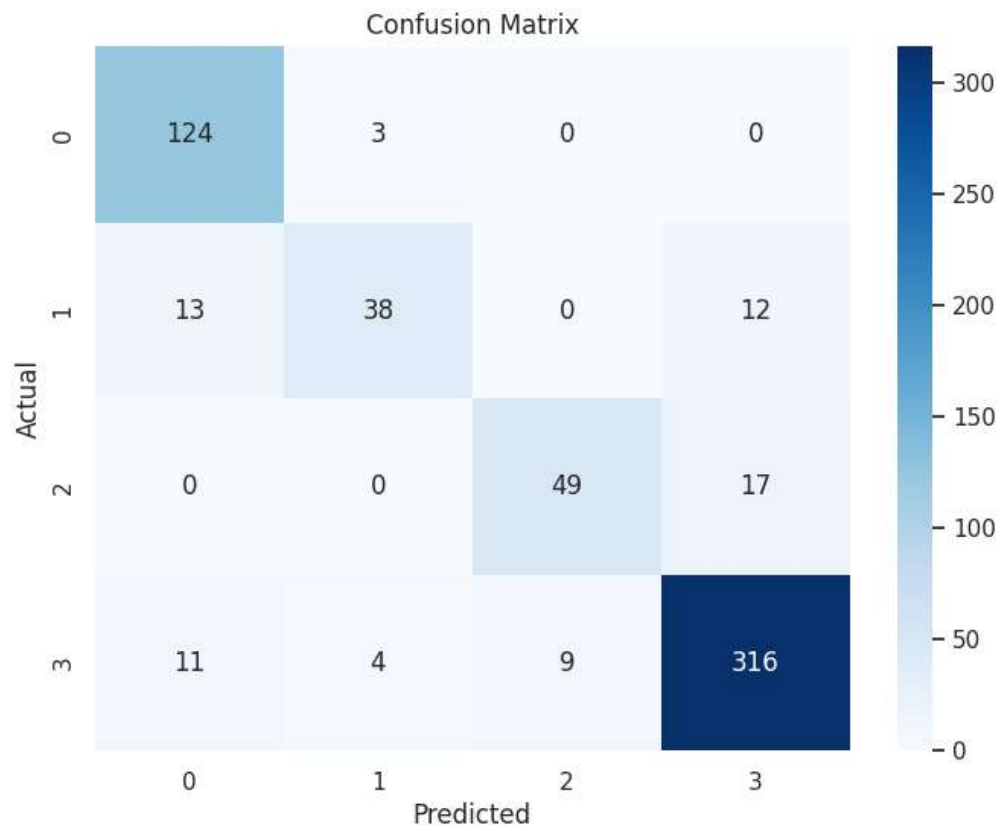


Figure14: Confusion matrix of l2 of logistic regression.[2]

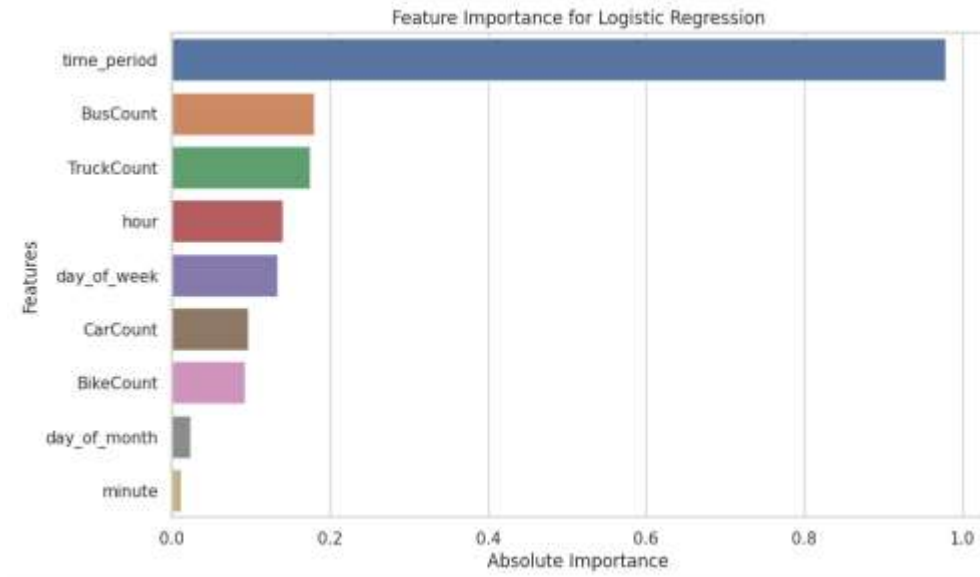
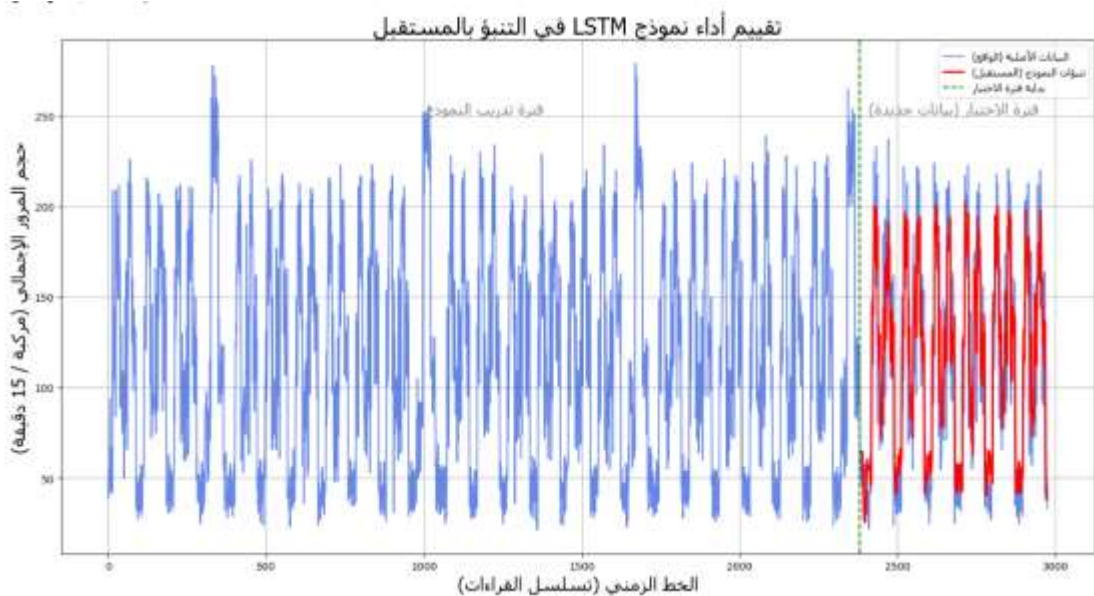


Figure14: feature importance of model2 [2]

In the logistic regression model, time period is the most important feature, highlighting its crucial role in traffic prediction. BusCount and TruckCount also appear to be of significant importance, while the hour and day_of_week contribute moderately. The number of vehicles, such as CarCount and BikeCount, has a smaller impact, emphasizing the model's focus on temporal factors for effective traffic management.

Time Series Forecasting Model (LSTM)



Chapter 6 Conclusion and Future Work

6.1 Conclusion

The random forest model is overfitted, and I solve it in a logistic regression model with L2-norm regularization. in terms of accuracy and generalization for traffic status prediction.

6.2 Important Features

The most influential features were CarCount, TruckCount, BusCount, and BikeCount especially, in first model RF.

The most influential features were time period, in second model logistic regression with l2 norm regularization.

6.3 Future Work

- Integrating weather data
- Using hybrid models
- Expanding the application

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