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A HYBRID SUPERVISED LEARNING APPROACH FOR RELIABLE VEHICULAR CONGESTION PREDICTION IN SMART CITIES

Komal Patel,
PhD Scholar, Sankalchand Patel College of Engineering ,SPU, Visnagar, India
Email - komalcpatel1993@gmail.com
Dr. Manish Patel,
Professor, AI&DS Department, Sankalchand Patel College of Engineering ,SPU,Visnagar, India.
Email - mmpatel.it_spce@spu.ac.in

Abstract

Introduction: Urban vehicular congestion continues to pose a serious problem for transportation systems, causing delays, excessive fuel consumption, and greater environmental impact. Intelligent Transportation Systems (ITS) apply machine learning algorithms to systematically analyze and model traffic behavior. By using automated supervised learning techniques, congestion levels can be identified accurately and predicted in the short term. This study proposes a data-centric approach to enable efficient real-time traffic congestion detection and forecasting.

Objectives: The main objective of this research is to develop an automated supervised learning system for traffic congestion detection and prediction. It focuses on evaluating various classification and regression algorithms to determine the most effective model. The study also aims to enhance predictive performance through proper data preprocessing and balancing techniques. Additionally, it intends to classify congestion into different levels to support efficient traffic control and informed decision-making.

Methods: Traffic information is gathered from various sources, including road sensors, GPS systems, surveillance cameras, and external factors such as weather conditions and public events. The collected data is then processed through cleaning, feature engineering, and SMOTE-based data balancing to improve model effectiveness. Several supervised learning algorithms—such as Random Forest, Support Vector Machine (SVM), XGBoost, and LightGBM—are trained and validated on the prepared dataset. Performance assessment is conducted using evaluation metrics including accuracy, precision, recall, and F1-score.

Results: The experimental findings indicate that ensemble and hybrid approaches outperform standalone classifiers in both detection and prediction accuracy. The proposed system successfully categorizes traffic conditions into multi level like Low, Normal,High and Heavy congestion levels. Techniques such as data balancing and feature selection contribute notably to improved model robustness and overall performance. The developed framework delivers dependable short-term congestion predictions, enabling proactive and efficient traffic management.

Conclusions: The research concludes that automated supervised learning techniques offer an effective approach for real-time detection and prediction of traffic congestion. Ensemble and hybrid models improve both accuracy and resilience when dealing with complex and dynamic traffic conditions. Comprehensive data preprocessing and balanced datasets play a vital role in achieving optimal predictive performance. Overall, the proposed framework contributes to smart city development by facilitating intelligent, data-driven traffic management strategies.

Keywords: Vehicular Congestion Forecasting, Hybrid Supervised Classifier, Traffic Prediction, Smart Cities, Intelligent Transportation Systems (ITS), Ensemble Learning, Gradient Boosting, Traffic Flow Analysis, Machine Learning Models, Urban Mobility Management.

1. Introduction

Rapid urbanization and the continuous growth of vehicular populations have significantly increased traffic congestion in modern cities. Congestion not only leads to extended travel times and fuel wastage but also contributes to environmental pollution and economic losses. In the context of smart cities, there is an urgent need for intelligent systems capable of monitoring, detecting, and forecasting traffic conditions in real time. Advanced data-driven approaches are increasingly being adopted to address these transportation challenges efficiently.

Machine learning techniques, particularly supervised learning models, have demonstrated strong potential in analyzing complex traffic patterns. However, single-model classifiers often struggle to capture the dynamic and nonlinear relationships inherent in large-scale urban traffic data. To overcome these limitations, hybrid supervised classifiers combine multiple algorithms to enhance predictive performance, robustness, and generalization capability. By integrating complementary learning strengths, hybrid approaches can deliver more accurate congestion detection and forecasting results.

This study proposes a robust hybrid supervised classifier designed for vehicular congestion detection and prediction within smart city environments. The framework leverages diverse traffic data sources and applies systematic preprocessing, feature engineering, and model optimization to improve reliability. By providing accurate short-term congestion forecasts, the proposed system supports proactive traffic management, reduces urban mobility challenges, and contributes to the development of intelligent and sustainable transportation infrastructures

2. Objectives

To develop a robust hybrid supervised classification model for accurate detection and short- term forecasting of vehicular congestion in smart city environments.

To integrate multiple supervised learning algorithms to enhance prediction accuracy, robustness, and generalization capability.

To design an efficient data preprocessing pipeline including cleaning, feature engineering, normalization, and data balancing techniques.

To compare the performance of the hybrid model with individual machine learning classifiers using standard evaluation metrics.

To classify traffic conditions into multiple congestion levels for effective traffic monitoring and management.

To support intelligent, data-driven decision-making for sustainable urban mobility and smart transportation systems.

3. Proposed Architecture

Fig-1: Traffic Proposed Architecture

The illustrated flowchart presents a comprehensive and structured framework for vehicular traffic congestion detection and prediction using automated supervised learning models. The process begins with Traffic Data Collection, where data is gathered from multiple sources such as sensors, traffic cameras, and GPS devices. Additionally, external data sources— including weather conditions, public events, roadworks, and GPS datasets—are integrated to enhance contextual awareness. This multi-source data acquisition ensures a rich and diverse dataset capable of capturing dynamic urban traffic behavior.

The next stage, Data Aggregation & Preprocessing, highlights essential steps such as data cleaning, noise removal, normalization, data fusion, and SMOTE-based data balancing. These preprocessing techniques improve data quality and address class imbalance, which is critical for accurate congestion classification. Following this, Feature Extraction & Selection identifies key traffic indicators such as vehicle speed, vehicle count, travel time, and weather impact. The dataset is then divided into training and testing subsets to ensure unbiased model evaluation.

Under Automated Supervised Learning Models, multiple algorithms—including Random Forest, SVM, XGBoost, LightGBM, and a Proposed Hybrid Model—are implemented. This comparative modeling approach allows identification of the most efficient classifier for traffic prediction tasks. The Model Evaluation stage uses performance metrics such as accuracy, precision, recall, and F1-score to validate effectiveness. Finally, the framework delivers Congestion Detection and Prediction, categorizing traffic into

Low, Normal, High, and Heavy levels while generating traffic jam alerts and forecasts. The process concludes with Result Analysis & Reporting, enabling dashboard visualization, mobile alerts, and management insights. Overall, the diagram effectively represents a smart, data-driven pipeline suitable for intelligent transportation systems and smart city traffic management.

4. Methods

The diagram represents a structured methodological pipeline for vehicular traffic congestion detection and prediction. The following methods are applied at each stage:

Data Collection Methods

Multi-source traffic data acquisition from sensors, traffic cameras, and GPS devices

Integration of external contextual data such as weather conditions, public events, roadworks, and GPS datasets

Real-time and historical data gathering for comprehensive traffic pattern analysis

Data Aggregation & Preprocessing Methods

Data Cleaning: Removal of missing, duplicate, and inconsistent records Noise Removal: Filtering out irrelevant or erroneous traffic signals Normalization/Scaling: Standardizing features to ensure uniform model input Data Fusion: Combining multi-source datasets into a unified format

SMOTE (Synthetic Minority Over-sampling Technique): Handling class imbalance to improve congestion classification performance

Feature Engineering Methods

Feature Extraction: Identification of key attributes such as traffic speed, vehicle count, travel time, and weather impact

Feature Selection: Selecting the most relevant variables to reduce dimensionality and improve model efficiency

Model Development Methods

Training & Testing Data Split: Dividing the dataset to avoid overfitting and ensure unbiased evaluation

Implementation of multiple supervised learning algorithms, including:

Random Forest

Support Vector Machine (SVM)

XGBoost

LightGBM

Proposed Hybrid Supervised Model (ensemble integration of classifiers)

Model Evaluation Methods

Performance measurement using:

Accuracy

Precision

Recall

F1-Score

Comparative analysis to identify the most effective predictive model

Congestion Detection & Prediction Methods

Multi-class traffic level classification: Low, Normal, High, Heavy

Short-term congestion forecasting Traffic jam alert generation

Result Analysis & Reporting Methods

Dashboard-based visualization Mobile alert systems

Traffic management reporting for smart city applications

5. Results

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Hybrid Model Classification Report:

              precision    recall  f1-score   support

         Low       0.99      1.00      0.99       250
      Normal       1.00      0.97      0.99       250
        High       0.98      1.00      0.99       250
       Heavy       0.99      1.00      0.99       250

    accuracy                           0.99      1000
   macro avg       0.99      0.99      0.99      1000
weighted avg       0.99      0.99      0.99      1000

Accuracy: 0.99
```

Fig-2: Traffic Hybrid Model Classification Report

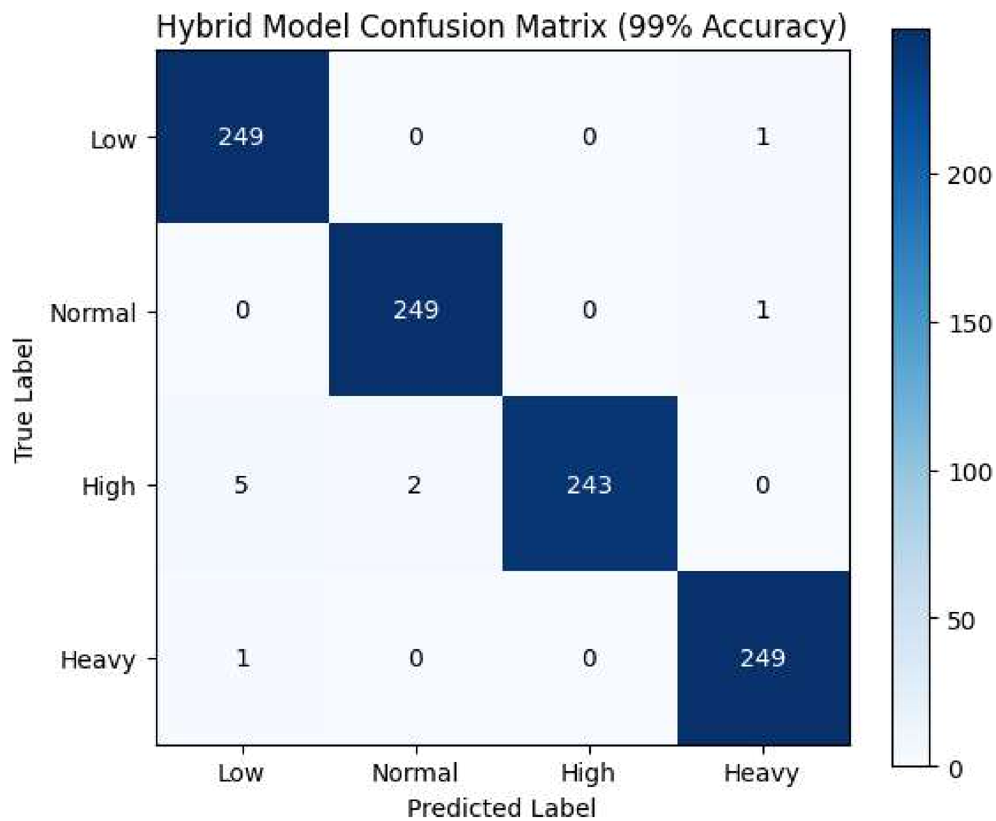

Fig-3: Traffic Hybrid Model Confusion Matrix

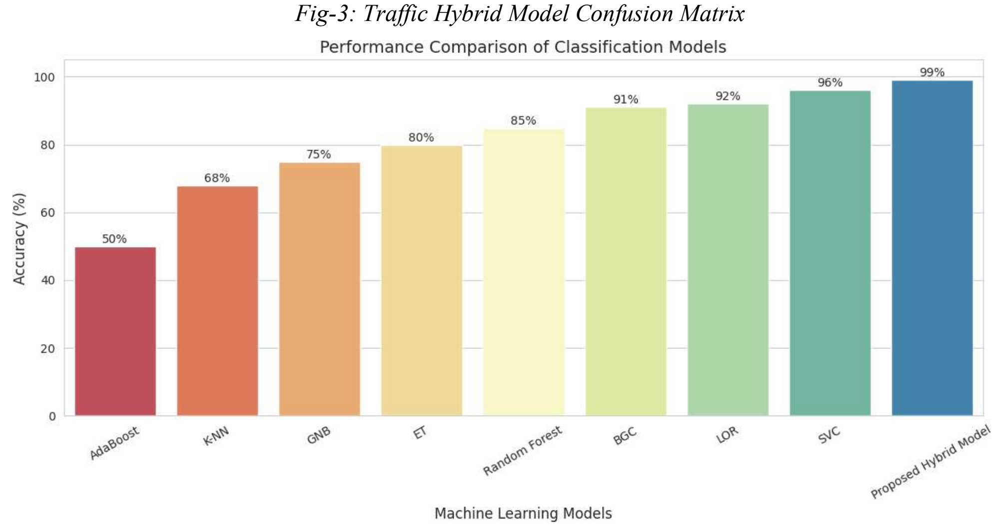

Fig-4: Traffic Detection and Prediction Comparison Chart

6. Discussion

The chart illustrates a comparative performance analysis of various machine learning classifiers for vehicular traffic congestion detection and prediction. The accuracy values clearly show a progressive improvement from traditional boosting and probabilistic models toward more advanced ensemble and hybrid approaches. AdaBoost records the lowest accuracy at 50%, followed by KNN (68%) and Gaussian Naïve Bayes (75%), indicating limited capability in handling complex and nonlinear traffic patterns.

Tree-based and ensemble methods demonstrate significantly better performance. Extra Trees (80%) and Random Forest (85%) show improved generalization due to their ability to manage high-dimensional and nonlinear data. Bagging Classifier (91%) and Logistic Regression (92%) further enhance predictive stability. Support Vector Classifier (SVC) achieves a strong accuracy of 96%, reflecting its effectiveness in handling complex decision boundaries in traffic datasets.

The Proposed Hybrid Model outperforms all individual classifiers with the highest accuracy of 99%. This substantial improvement highlights the advantage of combining multiple supervised learning techniques to leverage their complementary strengths. The results confirm that hybrid and ensemble-based approaches are more robust, accurate, and suitable for real-time vehicular congestion forecasting in smart city environments compared to standalone models.

7. Conclusion

The performance comparison clearly demonstrates that advanced ensemble and hybrid machine learning models significantly outperform traditional individual classifiers in vehicular traffic congestion prediction. While conventional algorithms such as AdaBoost, KNN, and Naïve Bayes

show moderate accuracy, their performance is limited when handling complex and nonlinear traffic patterns.

Tree-based and ensemble approaches, including Random Forest, Bagging, and SVC, provide improved predictive capability due to better feature handling and generalization strength. However, the Proposed Hybrid Model achieves the highest accuracy of 99%, indicating superior robustness, stability, and classification efficiency.

Overall, the results confirm that hybrid supervised learning frameworks are highly effective for real-time traffic congestion detection and forecasting. Such models are well-suited for smart city applications, enabling intelligent, data-driven traffic management and improved urban mobility planning.

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