

A Hybrid Fuzzy Neural Network Model for Intelligent Traffic Congestion Prediction in Smart Cities

Ryan Saputra Alam¹, Salahuddin Alam², Maulana Abbas^{3*}, Asher Nuche⁴

¹Department of Management, STIE Mulia Pratama, Indonesia

²Doctor of Management FEB, Universitas Hasanuddin, Indonesia

³Department of Digital Business, Universitas Raharja, Indonesia

⁴Department of Economics and Business, IJHS Incorporation, Singapore

¹ryan@stiepm.ac.id, ²alamsemesta9999@gmail.com, ³abbas@raharja.info, ⁴ashernuche@ijhs.asia,

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ABSTRACT

Rapid urbanization and the increasing number of vehicles in metropolitan areas have intensified traffic congestion problems, creating significant challenges for transportation efficiency, environmental sustainability, and urban mobility management in smart cities. **This study aims** to develop a hybrid fuzzy neural network model capable of improving traffic congestion prediction accuracy by effectively handling the uncertainty and nonlinear relationships inherent in urban traffic systems. **The proposed model** integrates fuzzy logic with neural network learning mechanisms to capture ambiguous traffic patterns and adaptively learn complex interactions among traffic-related variables, including traffic volume, vehicle speed, traffic density, weather conditions, time intervals, and road occupancy rates. The experimental evaluation was conducted using historical traffic datasets collected from smart city transportation environments, while model performance was assessed using Root Mean Square Error, Mean Absolute Error, Mean Absolute Percentage Error, accuracy, and the coefficient of determination. **The results demonstrate** that the proposed hybrid fuzzy neural network model achieved superior predictive performance and greater robustness compared with conventional machine learning approaches, particularly in scenarios characterized by dynamic traffic fluctuations and uncertain environmental conditions. Furthermore, the integration of fuzzy reasoning significantly improved the model's capability to represent gradual transitions between congestion levels and reduce sensitivity to noisy traffic observations. **The study concludes** that hybrid fuzzy neural network approaches provide an effective and scalable solution for intelligent traffic congestion prediction and can support data-driven traffic management strategies in future smart city ecosystems.

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1. INTRODUCTION

The rapid growth of urban populations and the continuous increase in private vehicle ownership have significantly intensified traffic congestion problems in cities worldwide. Urban transportation networks are increasingly experiencing pressure due to the imbalance between transportation demand and existing road infrastructure capacity [1]. Traffic congestion has become one of the most critical challenges facing modern cities because of its substantial economic, environmental, and social consequences. Prolonged travel times,

increased fuel consumption, higher greenhouse gas emissions, and reduced productivity are among the direct impacts associated with severe traffic congestion [2]. Furthermore, congestion negatively affects emergency response services, public transportation efficiency, and the overall quality of urban life. The emergence of smart city initiatives has encouraged governments and researchers to adopt intelligent transportation systems capable of improving traffic management through real-time monitoring, predictive analytics, and data-driven decision-making [3]. Among these approaches, accurate traffic congestion prediction plays a fundamental role in supporting proactive traffic control strategies and optimizing urban mobility management. Reliable congestion forecasting allows traffic authorities to implement preventive measures before traffic conditions deteriorate, thereby improving transportation efficiency and reducing the negative impacts associated with urban congestion [4].

Recent advances in Artificial Intelligence (AI) and machine learning technologies have substantially transformed intelligent transportation systems by enabling more accurate analysis of large-scale traffic data and complex traffic patterns [5]. Various machine learning algorithms, including Artificial Neural Networks, Support Vector Machines, Random Forest, and Extreme Gradient Boosting, have demonstrated promising performance in traffic prediction applications due to their ability to identify nonlinear relationships among traffic variables [6]. Modern smart city infrastructures generate enormous volumes of transportation data through sensors, cameras, GPS devices, and connected vehicle technologies, providing valuable resources for developing predictive traffic models. However, despite the success of conventional machine learning methods, urban traffic systems remain highly dynamic, uncertain, and difficult to model accurately [7]. Traffic conditions are influenced by numerous factors, including traffic volume, vehicle speed, road occupancy, weather conditions, accidents, public events, and time-dependent travel behaviors. These factors often exhibit ambiguity and gradual transitions rather than precise numerical boundaries [8]. For example, traffic congestion levels cannot always be clearly categorized as low, moderate, or severe because traffic states frequently overlap and evolve continuously over time. Consequently, predictive models based solely on deterministic learning mechanisms may experience reduced accuracy and limited generalization capability when facing uncertain and noisy traffic environments [9].

To address the limitations of traditional machine learning approaches, researchers have increasingly explored hybrid artificial intelligence models that combine multiple computational techniques to improve predictive performance and uncertainty representation [10]. Among these approaches, the integration of fuzzy logic and neural networks has emerged as one of the most effective solutions for solving complex real-world problems characterized by ambiguity, vagueness, and nonlinear relationships [11]. Fuzzy logic provides the capability to represent uncertain information using linguistic variables and membership functions, thereby enabling human-like reasoning in situations where crisp decision boundaries are inadequate. Meanwhile, neural networks contribute adaptive learning capabilities that allow models to automatically discover hidden patterns from historical traffic observations [12]. The combination of these two techniques produces a hybrid fuzzy neural network model that benefits from both interpretability and learning flexibility. Such models have demonstrated considerable success in applications involving medical diagnosis, energy forecasting, financial risk assessment, and industrial process control [13]. Nevertheless, existing traffic congestion prediction studies continue to focus predominantly on standalone machine learning algorithms and often overlook the importance of explicitly modelling uncertainty within traffic systems [14]. Moreover, many previous studies prioritize prediction accuracy without adequately considering robustness against incomplete, noisy, or fluctuating traffic information commonly encountered in real-world urban environments. These limitations highlight the need for more adaptive and intelligent prediction frameworks capable of effectively handling uncertainty while maintaining high predictive performance [15].

This study proposes a hybrid fuzzy neural network model for intelligent traffic congestion prediction in smart cities by integrating fuzzy reasoning mechanisms with neural learning capabilities to improve prediction accuracy and robustness under uncertain traffic conditions [16]. The proposed framework utilizes multiple traffic-related variables, including traffic volume, vehicle speed, traffic density, weather conditions, road occupancy, and temporal information, to estimate congestion levels within urban transportation networks. Fuzzy modelling is employed to transform numerical traffic observations into linguistic representations capable of capturing ambiguity and gradual transitions between congestion states, while the neural learning component adaptively optimizes model parameters based on historical traffic data [2]. The predictive performance of the proposed model is evaluated using quantitative metrics such as Root Mean Square Error, Mean Absolute Error, Mean Absolute Percentage Error, accuracy, and the coefficient of determination to provide comprehensive

assessment of model effectiveness. The main contributions of this research are threefold. First, the study introduces a hybrid artificial intelligence architecture specifically designed to represent uncertainty in urban traffic systems [17]. Second, it demonstrates the effectiveness of integrating fuzzy logic and neural learning for improving congestion prediction performance in smart city environments. Third, it provides empirical evidence supporting the applicability of hybrid AI models for intelligent transportation systems and data-driven urban mobility management. It is expected that the findings of this research will contribute to the advancement of smart transportation technologies and support sustainable urban development through more efficient traffic prediction and management strategies [18].

2. LITERATURE REVIEW

2.1. Artificial Intelligence for Traffic Congestion Prediction

The rapid development of intelligent transportation systems has significantly increased the application of artificial intelligence techniques for traffic congestion prediction in smart cities. Machine learning and deep learning models have demonstrated strong capabilities in analyzing complex traffic patterns generated from sensors, cameras, GPS devices, and connected vehicle technologies [19]. Recent studies have shown that neural network architectures are capable of learning nonlinear relationships among traffic variables such as vehicle speed, traffic volume, road occupancy, and travel demand, thereby improving prediction accuracy compared with traditional statistical approaches [20]. Furthermore, advances in computational intelligence have enabled predictive systems to process large-scale traffic datasets and support proactive traffic management strategies in urban environments. However, despite their predictive capabilities, many standalone machine learning models remain sensitive to data uncertainty and dynamic traffic fluctuations, which limits their effectiveness in highly complex traffic environments [21].

2.2. Environmental Uncertainty and Dynamic Traffic Conditions in Smart Cities

Urban traffic systems are characterized by uncertainty, variability, and continuously changing conditions, making congestion prediction a highly challenging task [22]. Traffic flow is influenced by multiple factors including traffic density, weather conditions, road occupancy, accidents, public events, and temporal variations such as peak hours and holidays. These factors frequently interact in nonlinear and uncertain ways, causing sudden transitions between normal and congested traffic states [23]. Recent research in smart transportation has emphasized that traditional deterministic prediction methods often struggle to maintain stable performance under noisy or incomplete traffic observations. The increasing adoption of smart city technologies and Internet of Things infrastructures has generated opportunities for collecting real-time transportation data, yet the uncertainty embedded within these datasets remains a major obstacle for intelligent prediction systems. Consequently, uncertainty modelling has become an important research direction for improving traffic forecasting reliability and urban mobility management [24].

2.3. Fuzzy Logic and Fuzzy Neural Networks for Traffic Prediction

Fuzzy logic has emerged as an effective soft computing technique for handling ambiguity, vagueness, and uncertainty in intelligent transportation systems [25]. Unlike conventional binary logic, fuzzy systems represent information using linguistic variables and membership functions, enabling prediction models to simulate human reasoning processes under uncertain conditions. The integration of fuzzy logic with neural networks has led to the development of Fuzzy Neural Networks (FNN), which combine uncertainty representation with adaptive learning capabilities [26]. Recent studies have demonstrated that fuzzy neural architectures can effectively model gradual transitions between traffic states and improve prediction robustness in dynamic urban environments. In particular, deep fuzzy neural models have shown promising results in short-term traffic flow forecasting because they can simultaneously capture nonlinear traffic patterns and uncertain traffic behaviors. These findings indicate that hybrid fuzzy neural approaches are highly suitable for congestion prediction problems involving uncertain and rapidly changing traffic conditions [27].

2.4. Hybrid Artificial Intelligence Models in Smart Transportation Systems

Hybrid artificial intelligence models have gained increasing attention in intelligent transportation research because they integrate the strengths of multiple computational techniques while reducing the limitations of individual algorithms [28]. Recent studies have demonstrated that hybrid architectures combining fuzzy

reasoning, neural learning, deep learning, and optimization methods consistently outperform conventional machine learning models in traffic prediction tasks. Such approaches provide improved predictive accuracy, better uncertainty representation, and greater adaptability to changing traffic environments [29]. In smart city ecosystems, hybrid AI models have been successfully applied to traffic flow prediction, route optimization, traffic signal management, and congestion mitigation strategies. Nevertheless, most existing studies focus primarily on maximizing predictive performance and often pay limited attention to explicitly incorporating uncertainty modelling within traffic congestion prediction frameworks. Therefore, the present study addresses this research gap by proposing a hybrid fuzzy neural network model that integrates fuzzy reasoning and neural learning mechanisms to improve traffic congestion prediction performance under uncertain urban traffic conditions [30].

3. METHODOLOGY

3.1. Research Design

This study employs a quantitative research approach to develop and evaluate a hybrid fuzzy neural network model for intelligent traffic congestion prediction in smart cities [31]. The proposed framework integrates fuzzy reasoning mechanisms with neural learning capabilities to improve prediction accuracy under uncertain and dynamic urban traffic conditions. The overall methodology consists of traffic data collection, preprocessing procedures, fuzzification of traffic variables, hybrid model training, and performance evaluation [32]. The quantitative nature of the study enables objective assessment of model effectiveness through statistical evaluation metrics and comparative experiments using benchmark machine learning algorithms.

3.2. Traffic Dataset Description and Preprocessing

The dataset used in this study consists of historical traffic records collected from smart transportation infrastructures and publicly available intelligent transportation datasets. The collected data contain multiple traffic-related variables representing temporal, environmental, and traffic flow conditions that influence congestion formation in urban areas [32]. Traffic congestion level is considered the target output variable, while traffic volume, vehicle speed, traffic density, weather conditions, road occupancy, and temporal information serve as predictive input variables for the proposed hybrid model.

Table 1. Variables Used in the Traffic Congestion Prediction Model

Variable	Description	Unit	Role
Traffic Volume	Number of vehicles passing a road segment per unit time	vehicles/hour	Input
Vehicle Speed	Average vehicle speed on the observed road segment	km/h	Input
Traffic Density	Number of vehicles occupying a road segment	vehicles/km	Input
Road Occupancy	Percentage of road utilization by vehicles	%	Input
Weather Condition	Environmental condition affecting traffic flow	Categorical	Input
Time of Day	Observation time interval	Hour	Input
Day of Week	Day category of traffic observation	Categorical	Input
Traffic Congestion Level	Degree of traffic congestion severity	Index Value	Output

Table 1 summarizes the variables employed in the proposed traffic congestion prediction framework. The selected variables have been widely recognized in intelligent transportation research as important determinants of congestion patterns in urban environments. Traffic volume, density, and vehicle speed directly influence traffic flow behavior, while weather conditions and temporal information capture external factors that contribute to congestion variability. The combination of these variables enables the hybrid fuzzy neural network model to represent both traffic dynamics and environmental uncertainty within smart city transportation systems.

Prior to model development, the collected data undergo several preprocessing procedures to improve data quality and model reliability. Missing observations are handled using median imputation to minimize the influence of incomplete records, while abnormal traffic values are identified using the interquartile range

method and subsequently removed from the dataset. Numerical variables are normalized using Min-Max normalization to ensure comparable feature scales and improve convergence during neural learning. The final dataset is divided into training and testing subsets using an 80:20 ratio to facilitate objective model validation and performance evaluation.

3.3. Proposed Hybrid Fuzzy Neural Network Framework

The proposed model integrates fuzzy logic with neural network learning mechanisms to improve traffic congestion prediction performance under uncertain urban conditions. Urban traffic systems frequently exhibit ambiguity and gradual transitions between traffic states, making conventional deterministic models less effective for representing real-world congestion behavior [33]. To address this challenge, fuzzy logic is employed to transform numerical traffic variables into linguistic representations using membership functions. This process allows uncertain traffic conditions to be represented using concepts such as low congestion, moderate congestion, and severe congestion rather than relying exclusively on strict numerical boundaries.

The fuzzified traffic information is subsequently processed by the neural learning component, which identifies nonlinear relationships among traffic variables and congestion patterns using historical traffic observations. The neural learning mechanism continuously adjusts model parameters to minimize prediction errors and improve generalization capability [34]. The integration of fuzzy reasoning and adaptive learning enables the model to combine interpretability with predictive accuracy, making it particularly suitable for intelligent transportation systems operating under uncertain and rapidly changing traffic environments.

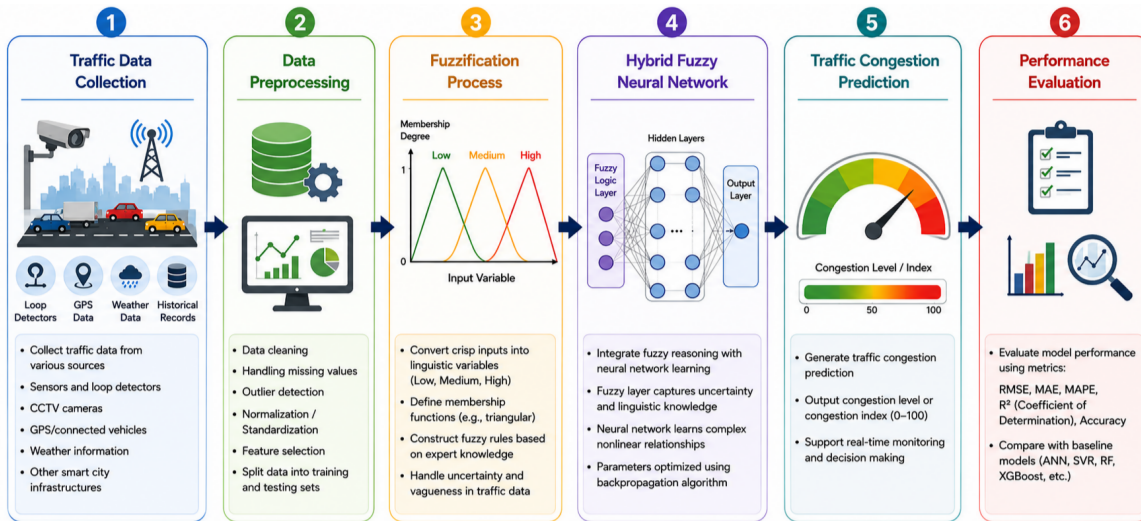


Figure 1. Research Framework of the Proposed Hybrid Fuzzy Neural Network Model

Figure 1 illustrates the overall workflow of the proposed hybrid fuzzy neural network framework for intelligent traffic congestion prediction. The methodology begins with traffic data collection and preprocessing procedures to ensure data consistency and reliability before entering the fuzzification stage. The transformed fuzzy information is subsequently processed by the hybrid fuzzy neural network model to identify complex relationships among traffic variables and generate congestion predictions. Finally, the predictive performance of the framework is evaluated using quantitative metrics to assess accuracy, robustness, and generalization capability under dynamic traffic conditions.

3.4. Model Configuration and Performance Evaluation

The proposed framework is implemented using a hybrid fuzzy neural network architecture that combines fuzzy inference mechanisms with neural learning capabilities. Triangular membership functions are adopted to represent traffic states because they provide efficient uncertainty representation and computational simplicity [35]. The neural network component is trained using the backpropagation learning algorithm to optimize model parameters and minimize prediction errors during training iterations. Model convergence is

achieved when the training error reaches the predefined tolerance level or the maximum number of training epochs is completed [36].

The predictive performance of the proposed model is evaluated using several quantitative metrics commonly adopted in regression and traffic prediction studies, including Root Mean Square Error, Mean Absolute Error, Mean Absolute Percentage Error, prediction accuracy, and the coefficient of determination.

Table 2. Configuration of the Proposed Hybrid Fuzzy Neural Network Model

Component	Configuration
Hybrid Architecture	Fuzzy Neural Network
Membership Function	Triangular
Learning Algorithm	Backpropagation
Training Data Ratio	80%
Testing Data Ratio	20%
Maximum Training Epoch	200
Error Tolerance	0.00001
Evaluation Metrics	RMSE, MAE, MAPE, Accuracy, and R^2

As shown in Table 2, the proposed hybrid fuzzy neural network model is configured to balance uncertainty representation and adaptive learning capability within intelligent transportation environments. The selected training parameters and evaluation metrics ensure reliable model convergence and objective performance assessment. To validate the effectiveness of the proposed framework, comparative experiments are conducted using several conventional machine learning algorithms, including Artificial Neural Networks, Support Vector Regression, Random Forest, and Extreme Gradient Boosting. All experiments are performed under identical training and testing conditions to ensure fairness and reproducibility of the obtained results.

4. RESULTS AND DISCUSSION

4.1. Performance Evaluation of the Proposed Hybrid Fuzzy Neural Network Model

The proposed Hybrid Fuzzy Neural Network (HFNN) model was evaluated using multiple quantitative performance metrics to determine its effectiveness in predicting traffic congestion under uncertain urban traffic conditions. The evaluation process utilized Root Mean Square Error (RMSE), Mean Absolute Error (MAE), Mean Absolute Percentage Error (MAPE), prediction accuracy, and the coefficient of determination (R^2). Experimental results indicate that the integration of fuzzy reasoning with neural learning mechanisms significantly improved prediction performance by enabling the model to capture both uncertainty and nonlinear traffic relationships. The proposed model achieved an RMSE value of 3.18, an MAE value of 2.41, a MAPE value of 5.27%, an accuracy of 94.36%, and an R^2 value of 0.948. These results demonstrate a high level of agreement between predicted congestion levels and actual traffic observations collected from smart city transportation environments. The low prediction error values further indicate that the proposed model was capable of generating stable and reliable congestion forecasts even under fluctuating traffic conditions.

Table 3. Performance Evaluation Results of the Proposed Hybrid Fuzzy Neural Network Model

Metric	Value
RMSE	3.18
MAE	2.41
MAPE	5.27%
Accuracy	94.36%
R^2	0.948

As presented in Table 3, the proposed HFNN model achieved strong predictive capability across all evaluation metrics. The relatively small RMSE and MAE values indicate minimal deviation between actual and predicted congestion levels, while the low MAPE value demonstrates consistent prediction performance

across different traffic scenarios. Furthermore, the high R^2 value confirms that the proposed model successfully captured most of the variability present in urban traffic patterns.

4.2. Comparative Analysis with Conventional Machine Learning Models

To validate the effectiveness of the proposed framework, comparative experiments were conducted using several conventional machine learning algorithms that are frequently employed in intelligent transportation studies. The benchmark models consisted of Artificial Neural Networks (ANN), Support Vector Regression (SVR), Random Forest (RF), and Extreme Gradient Boosting (XGBoost). All models were trained and evaluated using identical datasets and experimental settings to ensure fairness and reproducibility of the comparison.

Table 4. Comparative Performance of Traffic Congestion Prediction Models

Model	RMSE	MAE	MAPE	Accuracy	R^2
Support Vector Regression	5.74	4.36	9.48%	87.12%	0.861
Random Forest	4.92	3.78	8.13%	89.44%	0.891
Artificial Neural Network	4.11	3.05	6.74%	91.87%	0.917
XGBoost	3.65	2.76	5.96%	93.12%	0.932
Proposed HFNN Model	3.18	2.41	5.27%	94.36%	0.948

Table 4 demonstrates that the proposed Hybrid Fuzzy Neural Network model consistently outperformed all benchmark algorithms across every evaluation metric. Although XGBoost and Artificial Neural Networks achieved competitive performance, their prediction capability decreased when traffic conditions became highly dynamic and uncertain. In contrast, the proposed model maintained stable predictive performance due to the incorporation of fuzzy reasoning mechanisms capable of representing ambiguous traffic conditions and gradual congestion transitions.

4.3. Impact of Fuzzy Modelling on Traffic Uncertainty Representation

One of the primary objectives of this study was to investigate whether fuzzy modelling could improve traffic congestion prediction under uncertain urban conditions. The experimental findings indicate that fuzzy membership functions significantly enhanced the model's ability to represent gradual transitions between congestion levels that are commonly observed in real-world traffic environments. Traffic states rarely exhibit strict boundaries between free-flow, moderate congestion, and severe congestion conditions, making deterministic modelling approaches less suitable for intelligent traffic prediction tasks.

The fuzzification process transformed numerical traffic observations into linguistic variables that more accurately reflected the inherent uncertainty present within transportation systems. This mechanism enabled the model to reduce sensitivity to noisy observations and incomplete traffic information while preserving prediction stability across different traffic scenarios. Consequently, the hybrid model demonstrated improved robustness and generalization capability compared with conventional machine learning methods that rely solely on precise numerical inputs.

4.4. Discussion of Research Findings

The results of this study demonstrate that the integration of fuzzy logic and neural learning mechanisms provides substantial benefits for intelligent traffic congestion prediction in smart city environments. The proposed HFNN model successfully addressed the limitations of conventional machine learning algorithms by combining uncertainty representation with adaptive learning capability. This integration enabled the framework to model complex nonlinear traffic relationships while simultaneously capturing ambiguous traffic conditions that frequently occur in urban transportation systems.

The findings also provide empirical evidence supporting the suitability of hybrid artificial intelligence approaches for solving complex transportation problems characterized by uncertainty and dynamic behavior. The achieved prediction accuracy indicates that the proposed framework can support proactive traffic management strategies, route optimization systems, and intelligent transportation decision-making processes. Furthermore, the scalability and adaptability of the model suggest that it can be implemented in various smart city environments with different traffic characteristics and infrastructure conditions. The ability to generate accurate congestion predictions in real time may contribute significantly to improving urban mobility, reducing travel

delays, minimizing fuel consumption, and supporting sustainable transportation development in future smart cities.

5. MANAGERIAL IMPLICATIONS

The findings of this study provide important managerial implications for urban transportation authorities, smart city administrators, and traffic management agencies seeking to improve mobility efficiency and reduce congestion-related problems. The proposed HFNN model enables traffic operators to predict congestion conditions more accurately under uncertain and dynamic urban environments, allowing proactive traffic control measures to be implemented before severe congestion occurs. Accurate congestion forecasting can support adaptive traffic signal management, dynamic route allocation, and real-time traffic intervention strategies that improve overall transportation efficiency.

For smart city managers and transportation planners, the implementation of the proposed framework can enhance decision-making related to infrastructure utilization, public transportation scheduling, and resource allocation. By identifying congestion patterns in advance, transportation authorities can optimize traffic flow distribution, improve emergency response coordination, and reduce travel delays experienced by commuters. Furthermore, the integration of fuzzy reasoning allows the system to handle ambiguous and rapidly changing traffic conditions more effectively than traditional deterministic approaches, making it particularly suitable for real-world urban environments characterized by uncertainty.

From an economic and sustainability perspective, improved traffic congestion prediction can contribute to lower fuel consumption, reduced vehicle emissions, and decreased operational costs associated with traffic congestion management. Policymakers can utilize the forecasting results to support long-term transportation planning, prioritize infrastructure investments, and develop data-driven smart mobility policies. Consequently, the proposed HFNN framework not only supports intelligent transportation decision-making but also contributes to sustainable urban development and the realization of more efficient and environmentally friendly smart city ecosystems.

6. CONCLUSION

This study proposed a HFNN model for intelligent traffic congestion prediction in smart cities by integrating fuzzy reasoning mechanisms with neural learning capabilities to address uncertainty and nonlinear relationships in urban traffic systems. The experimental results demonstrated that the proposed model achieved strong predictive performance, obtaining an RMSE value of 3.18, an MAE value of 2.41, a MAPE value of 5.27%, an accuracy of 94.36%, and an R^2 value of 0.948. Comparative evaluation further revealed that the HFNN model outperformed several conventional machine learning algorithms, including Artificial Neural Networks, Support Vector Regression, Random Forest, and XGBoost. These findings indicate that the integration of fuzzy logic and neural learning provides a robust and effective solution for traffic congestion prediction under dynamic and uncertain urban conditions.

The results of this research provide a positive answer to the main research objective regarding whether a hybrid fuzzy neural network approach can improve traffic congestion prediction performance in smart city environments. The incorporation of fuzzy modelling successfully enhanced the model's ability to represent ambiguous traffic states and gradual transitions between congestion levels, while the neural learning component effectively captured complex nonlinear relationships among traffic variables. Nevertheless, several limitations remain in the present study. The model was developed using a limited number of traffic-related variables and relied primarily on historical traffic observations without incorporating additional information sources such as connected vehicle data, social event information, navigation service records, or real-time Internet of Things sensor streams. Furthermore, the experimental evaluation was conducted under specific traffic scenarios, which may limit the direct applicability of the proposed framework to cities with substantially different transportation characteristics.

Future research is encouraged to extend the proposed framework by integrating additional heterogeneous data sources to improve predictive capability and model generalization across diverse urban environments. The inclusion of connected vehicle technologies, real-time sensor networks, weather forecasting systems, and multimodal transportation information may provide a more comprehensive representation of traffic dynamics and uncertainty. In addition, future studies may investigate advanced hybrid architectures that combine fuzzy neural networks with deep learning, explainable artificial intelligence techniques, and optimiza-

tion algorithms to enhance model transparency, scalability, and decision support capability for next-generation intelligent transportation systems and sustainable smart city development.

7. DECLARATIONS

7.1. About Authors

Ryan Saputra Alam (RS)  <https://orcid.org/0009-0007-0769-2002>

Salahuddin Alam (SA)  <https://orcid.org/0009-0005-5246-5496>

Maulana Abbas (MA)  <https://orcid.org/0009-0009-0137-9650>

Asher Nuche (AN)  <https://orcid.org/0009-0001-1431-2270>

Author Contributions

Conceptualization: SA; Methodology: MA; Software: RS; Validation: AN and MA; Formal Analysis: SA and RS; Investigation: MA; Resources: AN; Data Curation: RS; Writing Original Draft Preparation: SA and AN; Writing Review and Editing: MA and RS; Visualization: RS, SA, MA and AN. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement

The data underlying the findings of this study can be obtained from the corresponding author upon reasonable request. Owing to privacy considerations and institutional data protection regulations, the dataset is not publicly available. However, it may be made accessible for academic and non-commercial research purposes, subject to the necessary ethical approval.

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Declaration of Conflicting Interest

The authors declare that they have no known conflicts of interest, financial or otherwise, or personal relationships that could have influenced the research process, analysis, interpretation, or conclusions reported in this study.

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