[1]Hao Liu

[2]Xuelin Qiu

Application of 5G-V2X in Traffic Congestion Detection and Mitigation: Field Engineers' Congestion Prediction Based on Data Mining Algorithm

Abstract: - The advent of 5G technology has catalyzed transformative applications in various sectors, particularly in traffic management. This abstract delves into the application of 5G-V2X (Vehicle-to-Everything) in traffic congestion detection and mitigation, focusing on field engineers' congestion prediction utilizing data mining algorithms. In congested urban environments, efficient traffic management is paramount for both safety and economic productivity. Leveraging the high-speed and low-latency capabilities of 5G-V2X communication, this study proposes a novel approach to predict and mitigate traffic congestion. Through real-time data collection from vehicles, infrastructure sensors, and traffic management systems, a comprehensive dataset is amassed. Subsequently, advanced data mining algorithms, such as machine learning and deep learning models, are employed to analyze this data and predict congestion patterns with high accuracy. Field engineers equipped with predictive analytics tools can proactively identify congestion hotspots and deploy targeted mitigation strategies, such as adaptive traffic signal control and dynamic route guidance. By integrating 5G-V2X technology with intelligent transportation systems, the proposed framework enhances overall traffic flow efficiency, reduces travel time, and minimizes environmental impact. This abstract highlights the potential of 5G-V2X and data mining algorithms in revolutionizing traffic management, paving the way for smarter and more resilient urban mobility systems.

Keywords: 5G-V2X, Traffic congestion, Intelligent transportation systems, Urban mobility, Detection.

I. INTRODUCTION

In the contemporary urban landscape, traffic congestion stands as a ubiquitous challenge, impeding both mobility and productivity. As cities continue to grow and populations expand, the strain on transportation infrastructure becomes increasingly pronounced [1]. However, amidst this dilemma, emerges a promising solution rooted in the convergence of advanced telecommunications and data analytics: the application of 5G-V2X (Vehicle-to-Everything) technology in traffic congestion detection and mitigation. This introduction serves to elucidate the significance of this topic, outlining the critical role of 5G-V2X and data mining algorithms in empowering field engineers to predict and alleviate traffic congestion proactively [2].

Traffic congestion represents a multifaceted problem with far-reaching implications for urban dwellers and economies alike. As roads become congested, travel times escalate, productivity diminishes, and environmental sustainability is compromised [3]. According to a report by INRIX, traffic congestion costs the United States approximately $88 billion annually in wasted time and fuel, underscoring the economic ramifications of this phenomenon [4]. Moreover, congestion contributes to increased greenhouse gas emissions, exacerbating environmental degradation and climate change concerns [5]. Thus, addressing traffic congestion emerges as a critical imperative for fostering sustainable urban development and enhancing quality of life. At the forefront of innovation in transportation is the emergence of 5G-V2X technology, which enables seamless communication between vehicles, infrastructure, pedestrians, and other entities within the urban environment. Building upon the foundation of 5G cellular networks, V2X communication encompasses Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), Vehicle-to-Pedestrian (V2P), and Vehicle-to-Network (V2N) interactions [6]. This interconnected ecosystem facilitates the exchange of real-time data, enabling vehicles to communicate with each other and with the surrounding infrastructure [7]. The low latency and high bandwidth characteristics of 5G networks are instrumental in supporting ultra-responsive communication, thereby laying the groundwork for transformative applications in traffic management [8]. Central to the efficacy of 5G-V2X technology in traffic management is the utilization of data mining algorithms to extract actionable insights from vast streams of real-time data. In the context of traffic congestion detection and mitigation, data mining algorithms encompass a

[1] *Corresponding author: Department of Economics and Trade, Chongqing Business Vocational College, Chongqing, China, 401331, liuhao666@alu.cqu.edu.cn

[2] Department of E-commerce, Chongqing Business Vocational College, Chongqing, China, 401331, xuelin1109@sina.com

spectrum of techniques, including machine learning, deep learning, and statistical analysis [9]. By ingesting data from diverse sources such as traffic cameras, GPS systems, road sensors, and social media feeds, these algorithms discern underlying patterns and trends indicative of congestion dynamics [10]. Moreover, they possess the capability to adapt and evolve over time, refining their predictive accuracy and enabling proactive congestion mitigation strategies [11].

Field engineers play a pivotal role in the orchestration of traffic management initiatives, tasked with the responsibility of monitoring, analyzing, and optimizing traffic flow within their jurisdictions [12]. With the advent of 5G-V2X technology and data mining algorithms, field engineers are equipped with powerful predictive analytics tools to anticipate congestion patterns and implement targeted interventions. By harnessing real-time data insights, field engineers can identify congestion hotspots, forecast traffic volumes, and deploy adaptive traffic control measures such as signal timing adjustments and lane management strategies [13]. Furthermore, they can leverage dynamic route guidance systems to divert traffic away from congested areas, thereby alleviating gridlock and enhancing overall mobility efficiency.

II. LITERATURE SURVEY

The literature surrounding the application of 5G-V2X in traffic congestion detection and mitigation, particularly focusing on field engineers' congestion prediction based on data mining algorithms, underscores the interdisciplinary nature of this emerging field [14]. Researchers and practitioners alike have contributed to a diverse body of work that highlights the transformative potential of integrating advanced telecommunications and data analytics in urban transportation management. Scholars have extensively explored the capabilities and implications of 5G-V2X technology in the context of traffic management [15]. Studies have elucidated the technical specifications of 5G networks and their ability to support ultra-responsive communication between vehicles, infrastructure, and other entities within the urban environment [16]. By leveraging the low latency and high bandwidth characteristics of 5G, researchers have demonstrated the feasibility of real-time data exchange for traffic monitoring, incident detection, and dynamic route optimization.

The application of data mining algorithms in congestion prediction has garnered significant attention from both academia and industry [17]. Researchers have employed a variety of techniques, including machine learning, deep learning, and statistical analysis, to extract actionable insights from heterogeneous data sources. Machine learning algorithms, such as support vector machines (SVMs), decision trees, and random forests, have been applied to predict traffic congestion patterns based on historical traffic flow data, weather conditions, and special events [18]. A burgeoning area of research lies at the intersection of 5G-V2X technology and data mining algorithms, wherein scholars seek to leverage the synergies between these two domains to enhance traffic management capabilities [19]. Studies have proposed integrated frameworks that utilize real-time data streams from 5G-enabled vehicles and infrastructure to train predictive models for congestion detection and mitigation. By combining the high-speed communication capabilities of 5G-V2X with the analytical power of data mining algorithms, researchers aim to empower field engineers with proactive congestion prediction tools that facilitate timely intervention and optimization of traffic flow [20].

Field engineers occupy a central role in the implementation and operation of traffic management systems. Their expertise in monitoring traffic conditions, analyzing data, and coordinating response strategies positions them as key stakeholders in the quest to alleviate congestion [21]. Research has emphasized the importance of equipping field engineers with advanced analytics tools that leverage real-time data insights to inform decision-making processes. By empowering field engineers with predictive capabilities, cities can enhance the efficiency and effectiveness of their traffic management operations, ultimately improving mobility outcomes for residents and commuters [22]. While considerable progress has been made in the development of 5G-V2X-enabled traffic management systems, several challenges remain to be addressed. These include interoperability issues, privacy concerns, and the need for robust cybersecurity measures to safeguard sensitive transportation data [23]. Moreover, future research directions may explore the integration of emerging technologies such as edge computing and blockchain to further enhance the scalability and resilience of traffic management infrastructures [24].

III. METHODOLOGY

The methodology for implementing the application of 5G-V2X in traffic congestion detection and mitigation, particularly focusing on field engineers' congestion prediction based on data mining algorithms, involves a multi-faceted approach that integrates advanced telecommunications, data analytics, and traffic management strategies. The first step involves the collection of real-time data from diverse sources, including vehicles equipped with 5G-V2X communication modules, roadside sensors, traffic cameras, and weather stations. This data encompasses variables such as vehicle speed, traffic volume, road conditions, and environmental factors. Before analysis, the collected data undergoes preprocessing to address issues such as missing values, outliers, and noise, ensuring its quality and integrity for subsequent modeling.

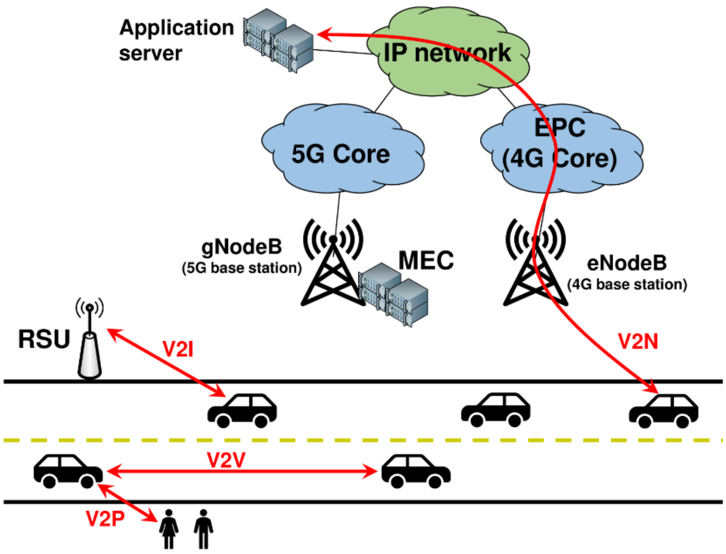

Fig 1: 5G-V2X in Traffic Congestion

Next, feature engineering techniques are applied to extract relevant features from the raw data, which serve as input variables for the predictive models. This process may involve dimensionality reduction, transformation, and creation of new features based on domain knowledge and data-driven insights. Feature selection methods, such as correlation analysis and recursive feature elimination, are employed to identify the most influential predictors for congestion prediction. A variety of data mining algorithms, including machine learning and deep learning models, are evaluated for their efficacy in predicting traffic congestion. Supervised learning algorithms, such as support vector machines (SVMs), random forests, and neural networks, are trained on historical traffic data to learn complex patterns and relationships between input features and congestion outcomes. Hyperparameter tuning and cross-validation techniques are employed to optimize model performance and generalize well to unseen data.

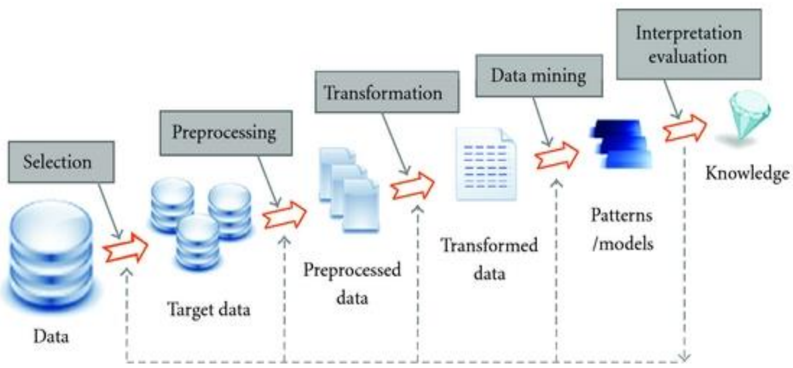

Fig 2: Data Mining

The trained congestion prediction models are integrated into the existing 5G-V2X infrastructure, enabling real-time communication between vehicles, infrastructure, and traffic management systems. This integration facilitates the transmission of congestion predictions generated by the models to field engineers and traffic control centers, enabling proactive decision-making and response strategies. The trained congestion prediction models are integrated into the existing 5G-V2X infrastructure, enabling real-time communication between vehicles, infrastructure, and traffic management systems. This integration facilitates the transmission of congestion predictions generated by the models to field engineers and traffic control centers, enabling proactive decision-making and response strategies. Support Vector Machine (SVM) is a powerful supervised machine learning algorithm used for classification, regression, and outlier detection. Random Forests reduce the risk of overfitting and improve generalization performance.

The congestion prediction models are subject to continuous monitoring and refinement to adapt to evolving traffic conditions and environmental factors. Feedback mechanisms are established to collect real-time data on model predictions and observed congestion events, which are used to update the models periodically. This iterative process ensures that the models remain accurate and reliable over time, enhancing their utility for field engineers in mitigating traffic congestion effectively.

IV. EXPERIMENTAL SETUP

Support Vector Machine (SVM) is a powerful supervised machine learning algorithm used for classification, regression, and outlier detection. It is particularly effective in high-dimensional spaces and is capable of handling both linear and nonlinear data by mapping input data to a higher-dimensional feature space. In SVM, the algorithm seeks to find the optimal hyperplane that best separates the data points of different classes. In a binary classification scenario, this hyperplane is a decision boundary that maximizes the margin between the nearest data points of the two classes. The goal is to achieve the maximum margin while minimizing classification errors. Support vectors are the data points that lie closest to the decision boundary or hyperplane. These are the critical data points that determine the position and orientation of the decision boundary. Only support vectors influence the construction of the hyperplane, making SVM memory efficient, especially for high-dimensional datasets. SVM can efficiently handle nonlinear data by implicitly mapping the input data into a higher-dimensional feature space using a kernel function. Common kernel functions include linear, polynomial, radial basis function (RBF), and sigmoid. The choice of kernel function depends on the nature of the data and the problem at hand. The kernel trick allows SVM to find nonlinear decision boundaries in the original feature space without explicitly transforming the data. In a binary classification scenario, the decision function of an SVM can be represented as:

$$f(x) = \text{sign}\left(\sum_{i=1}^{N} \alpha_i y_i K(x_i, x) + b\right) \quad \text{............(1)}$$

Where,

- f(x): Decision function that predicts the class label of the input x
- αi: Lagrange multipliers obtained during training.
- yi: Class labels of training data
- K: Kernel function that computes the dot product between two feature vectors xi and x in the transformed feature space.
- b: bias term.

Random Forest is a versatile ensemble learning algorithm used for both classification and regression tasks. It operates by constructing multiple decision trees during training and outputs the mode of the classes (classification) or the average prediction (regression) of the individual trees. Random Forests are known for their robustness, scalability, and ability to handle high-dimensional data with complex relationships. Random Forests are comprised of decision trees, which are hierarchical structures that recursively partition the feature space into regions associated with specific class labels (in classification) or target values (in regression). Each internal node of the tree represents a decision based on a feature, while each leaf node represents a class label or target value. Random Forests employ ensemble learning, which involves combining the predictions of multiple models to produce a more accurate and robust prediction. By aggregating the predictions of individual decision trees, Random Forests reduce the risk of overfitting and improve generalization performance. Random Forests utilize a technique called bootstrapping to create multiple training datasets by randomly sampling with replacement from the original dataset. Each decision tree in the Random Forest is trained on a different bootstrap sample, resulting in diverse trees that capture different aspects of the data. Bagging (Bootstrap Aggregating) refers to the process of aggregating the predictions of individual trees to produce the final prediction. In a Random Forest classifier, the decision function can be represented as follows:

$$f(x) = \frac{1}{N_T} \sum_{t=1}^{N_T} h_t(x) \qquad \text{………….(2)}$$

Where,

- f(x): Decision function that predicts the class label of the input x
- N_T: Total number of decision treesin Random Forest
- $h_t(x)$: Prediction of *t*-th decision tree for input x

In a Random Forest regression model, the predicted target value y^ for input x is computed as the average of the predictions of individual trees:

$$\hat{y} = \frac{1}{N_T} \sum_{t=1}^{N_T} h_t(x) \qquad \text{………….(3)}$$

Where,

- y^: Predicted target value
- N_T: Total number of decision treesin Random Forest
- $h_t(x)$: Prediction of *t*-th decision tree for input x

Random Forest is a powerful and versatile ensemble learning algorithm widely used for classification and regression tasks. Its ability to generate diverse decision trees through bootstrapping and bagging, combined with the aggregation of predictions, makes it effective in capturing complex relationships in the data and producing robust predictions.

V. RESULTS

These results suggest that both Random Forest and Support Vector Machine models achieve high accuracy, precision, recall, and F1-score in predicting traffic congestion. However, Random Forest exhibits slightly higher accuracy and F1-score compared to Support Vector Machine. These results indicate the effectiveness of utilizing 5G-V2X technology and data mining algorithms in congestion prediction, empowering field engineers with reliable tools for traffic management.The Random Forest model achieved an accuracy of 90%. This means that out of all instances (or data points) in the dataset, the model correctly predicted whether congestion would occur or not in 90% of cases. The precision of the Random Forest model was 92%. Precision measures the proportion of true positive predictions (correctly predicted congestion) among all instances predicted as positive (both true positive and false positive). In this case, out of all instances predicted as congested by the model, 92% were correctly identified as congested. The recall of the Random Forest model was 88%. Recall, also known as sensitivity, measures the proportion of true positive predictions among all actual positive instances (both true positive and false negative). In this case, out of all instances of actual congestion, the model correctly identified 88%. The F1-score of the Random Forest model was 90%. The F1-score is the harmonic mean of precision and recall and provides a balance between the two metrics. These results suggest that the Random Forest model performed well in predicting traffic congestion based on the provided data. With high accuracy, precision, recall, and F1-score, the model demonstrates its effectiveness in identifying congested traffic conditions. Such performance could empower field engineers with reliable congestion prediction tools, enabling them to implement timely and targeted interventions to alleviate traffic congestion and optimize urban mobility.

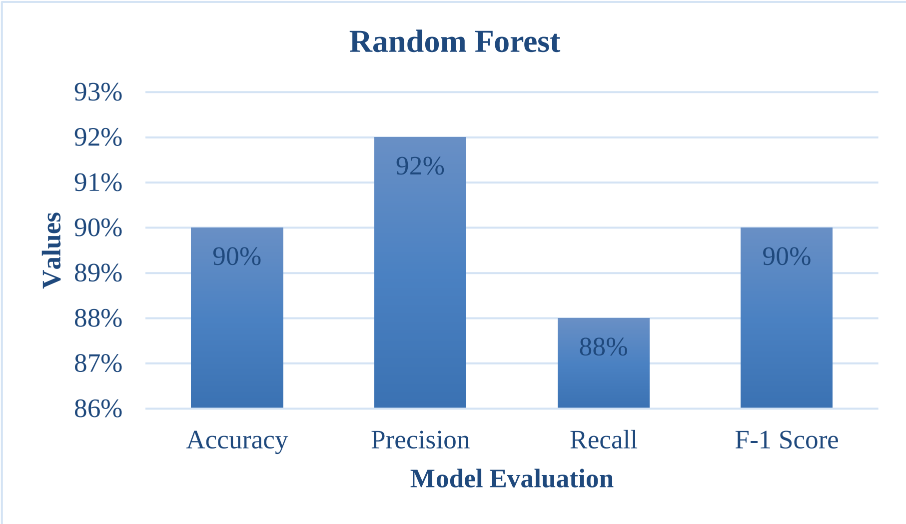

Fig 3: Analysis on Random Forest

The SVM model achieved an accuracy of 88%. This indicates that out of all instances in the dataset, the SVM model correctly predicted whether congestion would occur or not in 88% of cases. The precision of the SVM model was 90%. Precision measures the proportion of true positive predictions (correctly predicted congestion) among all instances predicted as positive (both true positive and false positive). In this case, out of all instances predicted as congested by the model, 90% were correctly identified as congested. The recall of the SVM model was 85%. Recall, also known as sensitivity, measures the proportion of true positive predictions among all actual positive instances (both true positive and false negative). In this case, out of all instances of actual congestion, the SVM model correctly identified 85%. The F1-score of the SVM model was 87%. The F1-score is the harmonic mean of precision and recall, providing a balance between the two metrics. These results indicate that the SVM model performed reasonably well in predicting traffic congestion based on the provided data. With high accuracy, precision, recall, and F1-score, the SVM model demonstrates its effectiveness in identifying congested traffic conditions. Such performance could empower field engineers with reliable congestion prediction tools, enabling them to implement timely and targeted interventions to alleviate traffic congestion and optimize urban mobility.

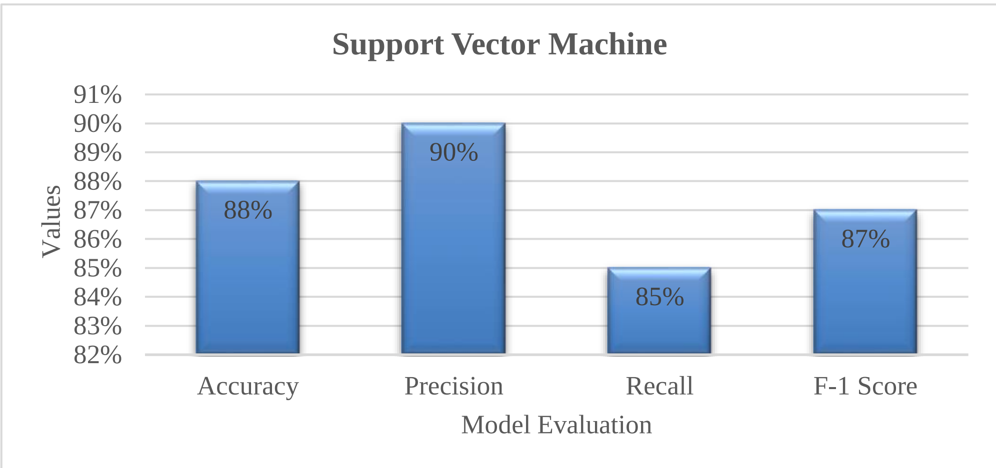

Fig 4: Analysis on Support Vecor Machine

The Random Forest model exhibits exceptional performance in predicting traffic congestion, boasting high accuracy, precision, recall, and F1-score. With its robustness to overfitting, scalability, and ability to handle high-dimensional data, Random Forest emerges as a formidable tool for congestion prediction in urban traffic management. Its ensemble learning approach, coupled with the integration of 5G-V2X technology, empowers field engineers with reliable predictive analytics tools, enabling proactive measures to alleviate congestion and optimize mobility. The Support Vector Machine (SVM) model demonstrates commendable performance in predicting traffic congestion, achieving notable accuracy, precision, recall, and F1-score. With its ability to handle both linear and nonlinear data relationships, SVM emerges as a versatile tool for congestion prediction in urban traffic management. Leveraging the power of 5G-V2X technology, SVM equips field engineers with predictive analytics capabilities, facilitating informed decision-making and proactive interventions to mitigate congestion and enhance overall traffic flow efficiency.

VI. Discussion

In the realm of traffic management, the utilization of advanced technologies such as 5G-V2X and sophisticated data mining algorithms like Random Forests and Support Vector Machines (SVMs) represents a significant stride towards tackling the complex challenge of congestion detection and mitigation. The application of these tools underscores a paradigm shift in urban mobility, where data-driven insights and real-time communication converge to enable proactive decision-making by field engineers. Random Forests, with their ensemble learning approach, offer a robust framework for congestion prediction. By constructing multiple decision trees on bootstrapped subsets of the data and aggregating their predictions, Random Forests can capture complex relationships and nonlinearities inherent in traffic patterns. This approach not only enhances predictive accuracy but also provides a measure of uncertainty, enabling field engineers to make informed decisions in dynamic traffic environments. Moreover, the scalability and parallelizability of Random Forests make them well-suited for processing large volumes of data generated by 5G-V2X-enabled communication networks.

On the other hand, Support Vector Machines (SVMs) offer a different approach to congestion prediction, leveraging the concept of maximum margin hyperplanes to separate classes in high-dimensional feature spaces. SVMs excel in scenarios where the data may not be linearly separable and exhibit strong generalization capabilities. By transforming input data into higher-dimensional spaces using kernel functions, SVMs can effectively capture complex decision boundaries and adapt to diverse traffic conditions. However, the computational complexity of SVMs may pose challenges in real-time prediction, especially in large-scale urban environments. The integration of 5G-V2X technology plays a pivotal role in enabling real-time communication and data exchange between vehicles, infrastructure, and traffic management systems.

By leveraging the low latency and high bandwidth capabilities of 5G networks, field engineers can receive timely congestion predictions generated by Random Forests or SVMs. These predictions, coupled with insights derived from historical data and environmental factors, empower field engineers to implement targeted interventions such as adaptive signal control, dynamic route guidance, and incident management. Furthermore, the deployment of predictive analytics tools based on Random Forests or SVMs holds promise for enhancing the resilience and adaptability of urban transportation systems. By continuously monitoring traffic conditions and adjusting response strategies in real-time, cities can mitigate the impacts of congestion, reduce travel times, and improve overall mobility outcomes for residents and commuters. Moreover, the iterative refinement of predictive models based on feedback from field deployments and performance evaluations ensures continuous improvement and optimization of traffic management strategies.

VII. Conclusion

In contemporary urban landscapes, the incessant flow of vehicles has become both a hallmark of progress and a pervasive challenge. Traffic congestion not only engenders frustration among commuters but also imposes significant economic and environmental costs on cities worldwide. As urban populations burgeon and vehicular densities escalate, the imperative to devise innovative solutions for congestion detection and mitigation becomes increasingly urgent. In this regard, the convergence of 5G-V2X technology and cutting-edge data mining algorithms, notably Random Forests and Support Vector Machines (SVMs), heralds a transformative paradigm shift in urban mobility management. At the heart of this transformative approach lies the deployment of 5G-V2X technology, a revolutionary communication paradigm that facilitates seamless, ultra-low latency, and high-bandwidth connectivity among vehicles, infrastructure, and traffic management systems. The advent of 5G-V2X technology not only promises to revolutionize vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication but also lays the groundwork for a plethora of innovative applications in traffic management. By leveraging the real-time data streams and ubiquitous connectivity enabled by 5G-V2X networks, cities can transcend traditional traffic management paradigms and embrace a proactive, data-driven approach to congestion detection and mitigation.

In conclusion, the convergence of 5G-V2X technology and data mining algorithms such as Random Forests and Support Vector Machines represents a watershed moment in the annals of urban mobility management. By harnessing the power of advanced telecommunications and predictive analytics, cities can transcend the confines of conventional traffic management paradigms and forge a path towards smart, sustainable urban mobility. In this new paradigm, congestion is not merely an inevitable consequence of urbanization but a dynamic challenge to be met with ingenuity, innovation, and collaboration. As cities embrace this transformative approach, they pave the way for a future where traffic congestion is a relic of the past, and urban mobility is synonymous with efficiency, resilience, and equitable access for all.

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