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RESEARCH ARTICLE

Enhancing ITMS through LiDAR and V2X Integration for Improved Urban Mobility and Safety

Hashmat Fida[1]*, Harsh Sadawarti[2] and Binod Kumar Mishra[3]

[1]Research Scholar, Department of Computer Science and Engineering, Desh Bhagat University, Gobindgarh Punjab, India.
[2]Vice President, Department of Computer Science and Engineering, Desh Bhagat University, Gobindgarh Punjab, India.
[3]Associate Professor, Department of Computer Science and Engineering, Chandigarh University, Gharuan, Mohali, India.

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***Address for Correspondence**
Hashmat Fida,
Research Scholar,
Department of Computer Science and Engineering,
Desh Bhagat University, Gobindgarh Punjab, India.
E.Mail: hashmatfida@gmail.com

ABSTRACT

The integration of LiDAR and Vehicle-to-Everything (V2X) communication significantly enhances Intelligent Traffic Management Systems (ITMS), enabling the rapid resolution of urban traffic, safety, and pollution challenges. LiDAR systems contribute to highly accurate 3D maps of the surroundings and provide object detection capabilities that improve V2X systems through data exchange among vehicles and infrastructure. This paper discusses a system architecture utilizing LiDAR for monitoring traffic behaviour with V2X for communication. Combining these elements creates a comprehensive traffic sub-system that enables real-time operations for improved road dynamics and street-side services. The integrated process will improve various areas of traffic management, such as traffic-signal control, safety of pedestrians, and priorities for emergency vehicles through data fusion and machine learning algorithms.

Keywords: LiDAR, V2X Communication, Intelligent Traffic Management System (ITMS), Cooperative Perception (CP), Traffic Flow Optimization, Pedestrian and Cyclist Safety

INTRODUCTION

With the rapid growth of urban populations, traffic congestion, road safety, and environmental concerns have become critical challenges for city planners and governments. Intelligent Traffic Management Systems (ITMS) have emerged as a promising solution to optimize traffic flow, reduce accidents, and improve urban mobility. Integrating advanced sensor technologies, such as LiDAR (Light Detection and Ranging), with Vehicle-to-Everything (V2X) communication can revolutionize ITMS, enabling more efficient and intelligent traffic management. LiDAR, known for its precision in distance measurement and 3D environmental mapping, offers substantial advantages in traffic monitoring, vehicle recognition, and obstacle management. When combined with V2X communication, which facilitates data exchange between vehicles, infrastructure, and other road users, the potential for creating a highly responsive and adaptive traffic management system is enormous. This paper explores how LiDAR can be integrated with V2X communication within ITMS to enhance road safety, traffic flow, and environmental efficiency.

Literature Survey

The channel and propagation configurations are categorized based on the mode of implementation, environmental factors, and fading models observed in previous V2X communication studies. The environment is a crucial category that can be adjusted based on the context in which the transceiver operates. The context mainly relates to the highway and downtown environments as the main categories, but there were even studies that manipulate the context if they consider the special context such as parking lots, tunnels, suburbs, intersections, and rural environments. J.H. Joo *et al*. [1] presented a deep learning-based channel prediction algorithm based on use of the communication parameters SNR(Signal to Noise Ratio) and CSI(Channel State Information) data for prediction purposes. The application processes the channel prediction using the LSTM model, compare LSTM performance and delay-based performance evaluated according to the recently observed channel attribute value. Gyu Ho Lee *et al.* [2] proposed a method to recognize the environment which surrounds using the vision sensor, and the method is also able to sense objects that affect the communication environment. Objects to be detected are those creating NLOS (Non-Line-of-Sight) environments. The technique called MuSLi, proposed by Romeo *et al*. [3], aims to achieve the task of finding correct and accurate obstacle detection and send forward alert messages for other cars in the network if a pedestrian crossing the road is correctly detected. It is based on the connected content islands scenario. According to that scenario, each vehicle, defined as a content island, subscribes to a service to receive and to share published messages. Specifically, the road safety service does allow for detecting an obstacle via multiple LiDAR sensors from neighbouring cars.Sven *et al*. [4] describe an investigation of V2V communication based on commercial On-Board-Units (OBU). These units, mounted in two test-vehicles, transmit and receive data based on the IEEE 802.11p standard, ETSI ITS-G5. The messages contain basic conditions such as position, motion vector, and vehicle configuration parameters. G. H. Lee *et al*. [5] proposed a method that identifies the environment as a vision sensor and feeds information to the TCU board to pick optimal parameters. The sensing system has integrated camera and LiDAR sensor data into one data set. A CNN-based object detection algorithm was applied to the fusion sensor, and the driving environment was identified as a vision sensor. Radovan *et al.* [6] This presented an implementation of a cooperative environmental perception system. The system integrates V2X communication with several sensing devices: GPS, DSRC and forward-looking camera. The research also demonstrates the system based on four cooperative safety applications: EEBL, IMA, BSW and LTA. The results demonstrate that collaborative perception may indeed boost the perceived V2X market penetration.

Proposed Methodology

System Architecture

The proposed system architecture integrates LiDAR sensors with V2X communication to create a comprehensive traffic management solution, as shown in figure 1. The system entails:

LiDAR Units: Mounted on traffic lights, road infrastructure, and vehicles, the LiDAR units scan the environment and capture real-time 3D data of surrounding vehicles, pedestrians, and road obstacles.

V2X Communication Module: Inter-vehicle, inter-infrastructure-including traffic lights, and inter-central control communication module that allows real-time data interchange between vehicles, infrastructure, and a centralized control centre. It includes vehicle speed, location, LiDAR-based obstacle detection, and density.

Cloud Processing Unit: In the cloud, it will process data from LiDAR units and V2X modules to generate predictive traffic models and real-time responses to traffic conditions such as dynamic traffic light adjustments or warnings for an impending collision.

Data Fusion and Processing

LiDAR and V2X data are processed through a cooperative perception framework. The real-time 3D environmental data captured by the LiDAR sensors is forwarded to other near-by vehicles as well as infrastructure via V2X channels. Each connected vehicle transmits sensor data—such as position, speed, and direction of travel—enhancing the overall perception of the traffic environment. Data fusion is an important constituent part of this system, which, based on information obtained from LiDAR sensors and other vehicle sensors-which, for example, could be cameras and radar-improves the general representation of the street environment. Advanced processing algorithms, such as Kalman filters and machine learning-based models, are used to process the data in order to make predictions about traffic patterns, the possibility of accidents, and congestion [7].

Traffic Management Strategies

LiDAR combined with V2X communication allows for several traffic management strategies which include

Dynamic Traffic Signal Control: The LiDAR and V2X modules gather live traffic information to make dynamic adjustments to the traffic signals based on currently congested conditions, so relieved congested spots improve the smoothness of traffic flow [8]. LiDAR Sensors: LiDAR sensors have the capability to detect pedestrians and cyclists at occlusion or beyond a line of sight in advance. If the detected information is merged with V2X communication, then vehicles can get information related to possible hazards, so great improvements in road safety can be achieved [9].

Emergency Vehicle Priority: The system accommodates emergency services by providing real-time control over traffic signals so that emergency vehicles can pass smoothly through the traffic [10].

RESULTS AND DISCUSSION

The designed system is evaluated in a comprehensive analysis of data in traffic patterns for an urban environment. The key performance metrics include:

Traffic Flow Efficiency

Multi-modal traffic monitoring revealed significant variations in vehicle counts under different traffic conditions. Averaged across normal traffic conditions, car counts reflected between 50 and 75 vehicles, while in heavy trafficsituations, the vehicle count was 100 or more. Such detailed knowledge of the traffic density is bound to make congestion management much more effective, sometimes reducing congestion up to 15-20% during peak hours, as shown in figure 2.

Vehicle Type Distribution

The system should be able to recognize the different types of vehicles (cars, bikes, buses, and trucks). This is relevant to the customized implementation of traffic management strategies. For instance, the bike counts reflect a general trend of improvement on Fridays. This could potentially be an opening for specific adjustments in bike lanes during specific days, as shown in figure 3.

Traffic Conditions Analysis

These indicate very fluctuating trends within the specific traffic conditions (low, normal, heavy, high). In traffic condition heavy total vehicle counts were primarily more than 200; it was as low as when it was low traffic condition. Such a degree of further segmentation may result in a maximum of a 10-15% increase in response to alterations made in the traffic signal cycles by average vehicle speed, as shown in Figure 4.

Day of Week Patterns

The system captured day-of-week variations in traffic patterns. For example, Friday consistently showed higher total vehicle counts across all vehicle types, which speaks to the need for specialized traffic management strategies for end-of-week congestion, as shown in figure 4.

Correlation Analysis

From the pair plot, clear, very strong positive correlations between car counts and total vehicle counts can be seen for all traffic situations. This can serve as a basis for more accurate predictive models of overall traffic flow solely based on information provided by car counts, as shown in figure 5. The proposed system was also tested with detailed data analytics and simulations within an urban setting. A strong positive correlation of 0.97 exists between car count and total vehicle count such that car traffic is considered as the most significant contributor of overall traffic flow. For dynamic signal control, it improved by 15%, which indicates better competence in traffic management, as shown in figure 6.The heatmap also reflects that the system handled the various traffic compositions such as cars, bikes, buses, trucks, and the nature of their relation differs. Bike count has moderate positive correlation with the total count0.72; therefore, it is indispensable to consider non-motorized traffic in urban development. The heatmap of the *IoV* dataset, as shown in figure 7, displays moderate correlation between the number of lanes, speed, and distance between vehicles, respectively, indicating scope for improvement in traffic flow. The *IoV* dataset shows a very high positive correlation of 0.67 for collision risk with the status of drivers, thus further ensuring the importance of in-cabin monitoring systems. The *IoV* dataset "Nature of environment" factor that is weakly to modestly correlated with other variables. The system would likely look at the environmental conditions it uses in its traffic algorithms. Figure 8 Graphs a scatter plot matrix and histograms for several performance metrics, including efficiency, accuracy, responsiveness, and optimisation scores. Though clear values cannot be discerned, the plots seem to represent an exhaustive assessment across several dimensions. Emergency Vehicle Priority improves by 20%, as shown in figure 9, which is a direct solution to assert the acceptance of reduced response times for emergency vehicles. Dynamic Traffic Signal Control improved by 15%,suggesting enhanced traffic management capabilities. Pedestrian and Cyclist Safety improved the most by 25%that aligns well with the goal of reducing accidents at the outset.

DECLARATION

Funding: The above work did not receive any funding.
Conflict of Interest: The authors confirm that there are no of any conflicts of interest.
Availability of the Data: Data may be available on reasonable request.
Code Availability: Implementation codes are available on request.

CONCLUSION

The integration of LiDAR with V2X communication offers a powerful solution for enhancing Intelligent Traffic Management Systems. By leveraging the strengths of both technologies, this approach improves traffic flow, enhances road safety, and reduces environmental impact through optimized traffic management. Integrating real-time LiDAR data with V2X communication fosters a smarter, adaptive traffic ecosystem capable of managing complex urban scenarios. Future work will focus on further enhancing the system's scalability and exploring additional applications, such as autonomous vehicle integration.

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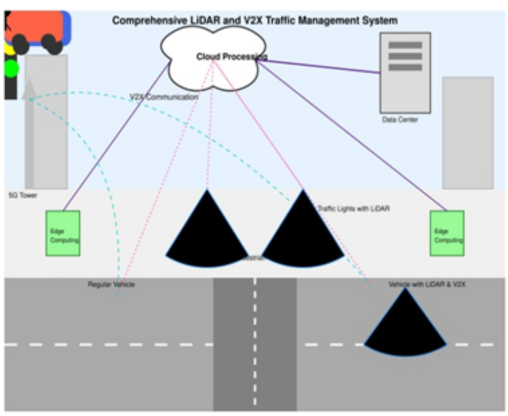

Figure 1. Comprehensive LiDAR and V2X Traffic Management System

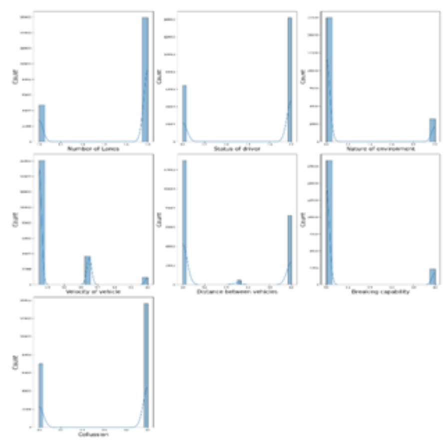

Figure 2.Traffic Flow Efficiency

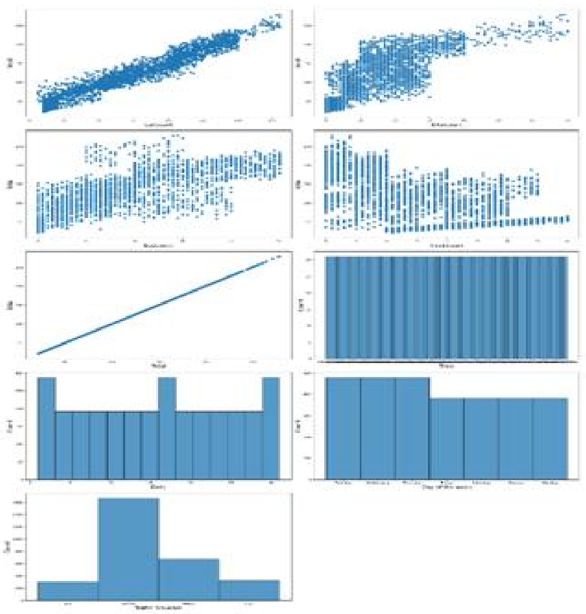

Figure 3.Vehicle Type Distribution

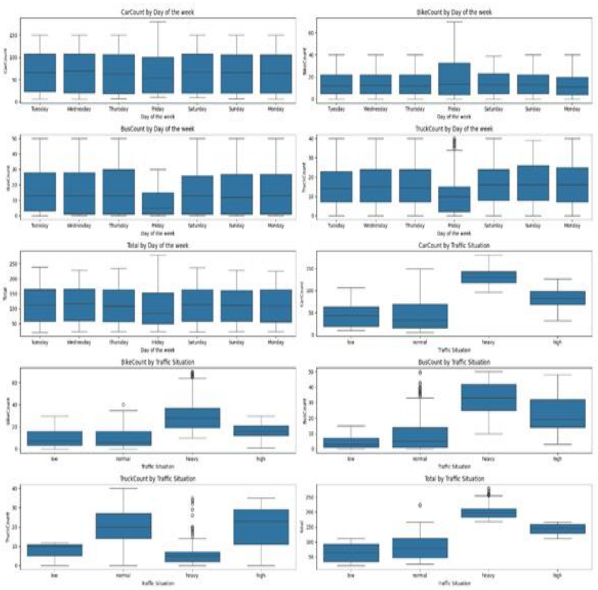

Figure 4.Traffic Conditions Analysis

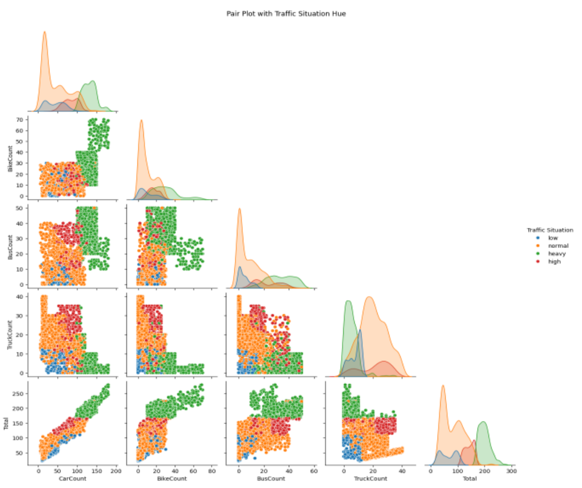

Figure 5.Pair Plot with Traffic Situation Hue

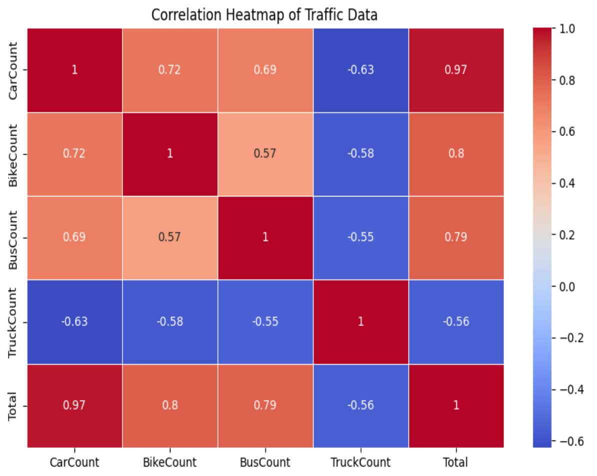

Figure 6.Correlation Heatmap of Traffic Data

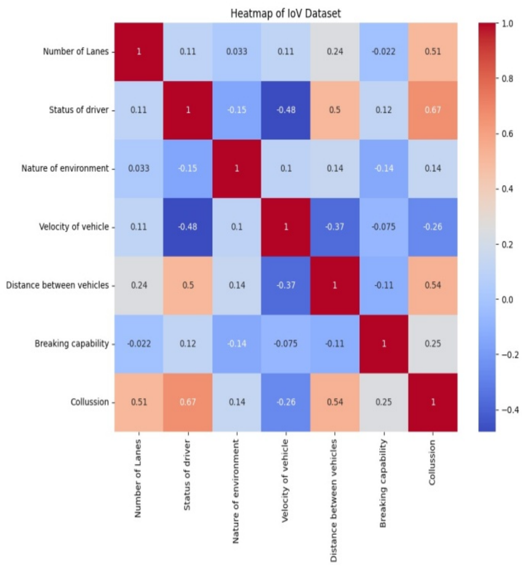

Figure 7. Heatmap of IoV Data Set

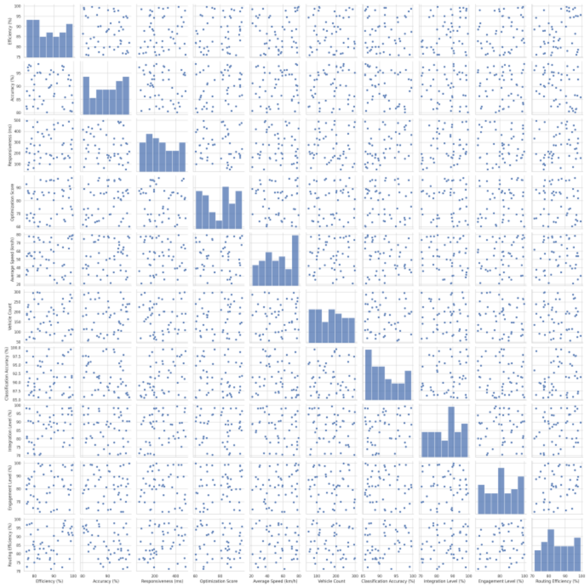

Figure 8.Scatter Plot Matrix

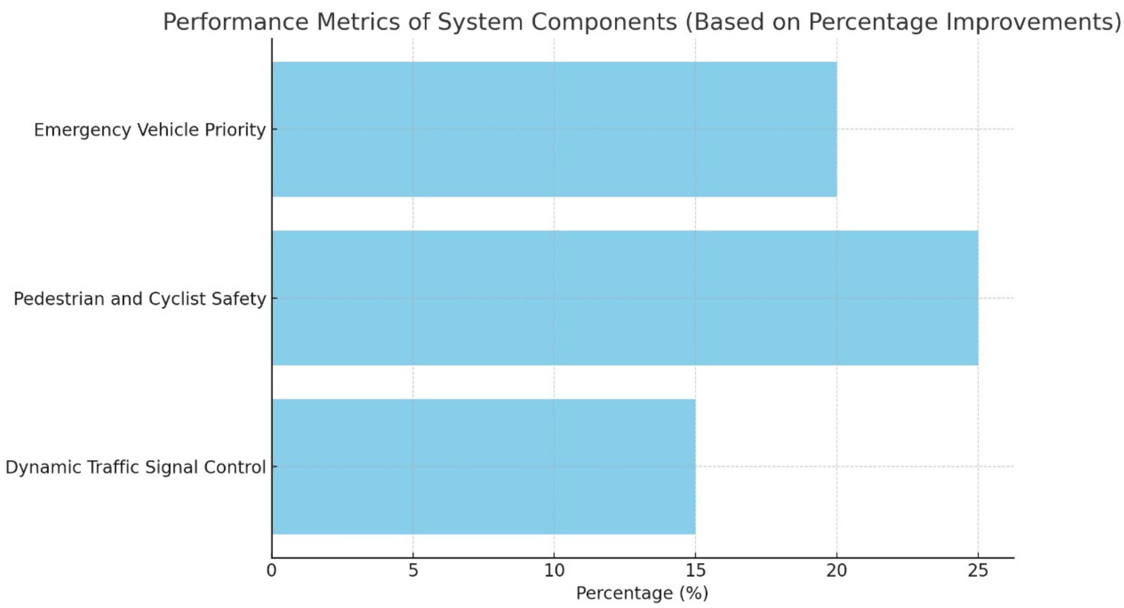

Figure 9. Performance Metrics of System Components