FlarePath: Advanced Vehicle Fire Safety and Monitoring with Rapid Emergency Dispatch Solutions

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***Abstract*—Vehicle fires pose serious risks, often resulting in severe damage and potential fatalities. Current detection systems are primarily reactive, failing to predict and mitigate fire hazards in advance. This research proposes an integrated solution that combines IoT, machine learning, and cloud computing to enhance vehicle fire safety and emergency response. The system uses IoT-enabled sensors to monitor fire indicators like smoke, temperature, and vibrations. Machine learning algorithms analyze this data for early fire prediction, while real-time fire information and vehicle location are transmitted to the nearest fire department, optimizing emergency response with real-time and historical traffic data. An IoT-based automatic fire extinguisher mechanism is implemented to reduce fire impact immediately upon detection. The methodology involves installing sensors, processing data with machine learning, and relaying it to the cloud for analysis. Alerts inform drivers and owners about fire incidents and nearby extinguishers, improving response times. The proposed solution significantly enhances fire safety, demonstrating high accuracy in fire prediction and severity classification.**

***Index Terms*—Fire Detection, Emergency Response, Fire Prediction, Automatic Fire Extinguishers, Fire Severity Classification, Proactive Safety Measures, Vehicle Safety Systems, Fire Incident Mitigation.**

I. Introduction

A. Overview of Vehicle Fire Safety Concerns

Vehicle fires are a significant safety concern that poses risks to occupants, surrounding infrastructure, and the environment. The causes of vehicle fires can range from mechanical failures and electrical malfunctions to external factors such as accidents and arson. Specifically, mechanical failures that can lead to fires include overheating engines, fuel system leaks, or worn-out components such as brakes and bearings that generate excessive heat. These failures create conditions where flammable materials like oil or fuel can ignite, causing a fire.

Despite the advancements in vehicle technology, existing fire detection systems are often reactive rather than proactive. Current systems typically alert occupants only after a fire has started, leaving little time to mitigate damage or evacuate safely. Moreover, these systems may not be optimized for the specific conditions and constraints of the automotive environment, leading to delayed detection and inadequate response measures, such as slower identification of the fire's source or delayed activation of fire suppression systems, which can result in the fire spreading more quickly and causing greater damage.

B. Importance of Rapid Emergency Dispatch Solutions

The effectiveness of emergency response is crucial in mitigating the impact of vehicle fires. Rapid dispatch of emergency services can significantly reduce damage and save lives. However, traditional emergency response systems in Sri Lanka often rely on manual communication methods, such as phone calls and radio dispatch, with limited access to real-time data. This can lead to delays in coordinating response efforts and inefficient use of resources, as the information is not always up-to-date or readily available.

By leveraging real-time data from sensors, predictive analytics, and automated emergency dispatch, these technologies can provide a more comprehensive and efficient approach to vehicle fire safety.

C. Objectives of the Research

This research aims to develop an advanced vehicle fire safety and monitoring system with rapid emergency dispatch solutions. The primary objectives are:

1) **Develop an Integrated Solution for Vehicle Fire Safety:** Create a system that combines IoT, ML, and cloud computing to provide comprehensive fire safety for vehicles. This includes detecting potential fire hazards, and initiating preventive measures.
2) **Implement Real-Time Emergency Dispatch Solutions:** Develop a cloud-based system to relay fire infor-

mation and vehicle position to the nearest fire department in real-time. Optimize emergency response routes using real-time traffic data and historical traffic patterns.

3) **Enhance Fire Severity Assessment:** Develop methods to accurately classify the severity of vehicle fires using sensor data and ML models. Provide real-time updates on fire severity to emergency responders and vehicle occupants.
4) **Integrate Automatic Fire Extinguishing Systems:** Implement IoT-enabled automatic fire extinguishers that activate upon detecting a fire, reducing the impact of the fire and potentially saving the vehicle and occupants.

The research seeks to enhance vehicle safety, reduce the impact of fires, and improve the efficiency of emergency responses, ultimately contributing to safer and more resilient automotive systems.

II. LITERATURE REVIEW

The studies provided valuable insights into the advancements and practical applications of these technologies in improving fire safety.

A. IoT-Based Fire Detection and Management Systems

1) IoT-Based Fire Protection System: .

The study titled "IoT Based Fire Protection System" introduced a comprehensive fire management system designed to track different kinds of fire incidents across industries. This system leverages various sensors, including smoke, heat, humidity, and flame detectors, to monitor fire conditions dynamically. This integration ensures a quick and reliable response, with significant improvements in alert accuracy and response times. [7]

2) Fire Detection and Control System Using Fuzzy Logic: In "Design and Implementation of a Fire Detection and Control System for Automobiles Using Fuzzy Logic," the authors developed a system that utilizes fuzzy logic to enhance fire detection and response. While this approach has significantly reduced the rate of false alarms and ensured timely and accurate fire detection with high classification accuracy in real-world conditions, it still exhibits certain limitations. [3]

3) Multi-Stage Early Warning System for Automobile Fire: The study "Research on Multi-Stage Early Warning System for Automobile Fire" focused on early fire detection in vehicles. It implemented a multi-layered approach, integrating temperature, smoke, and light sensors with an A/D converter and a single-chip microcomputer. This system provided early warnings and timely interventions by accurately detecting the initial signs of fire. The multi-stage detection process significantly improved the system's capability to detect fires at their inception, reducing the potential damage and enhancing vehicle safety. [1]

B. Multi-Degree Rotating Fire Extinguisher Systems

1) Design and Implementation of IoT-Based Multi-Degree Rotating Fire Extinguisher System: Chandramohan P. and other authors introduced a multi-degree rotating fire extinguisher system in their study "Design and Implementation of IoT Based Multi Degree Rotating Fire Extinguisher System." This system comprises a network of pipes, nozzles, and valves controlled by a central pump, distributing fire extinguishing agents like water or foam. The study demonstrated the system's high effectiveness in providing rapid and thorough fire suppression, making it suitable for both industrial and residential settings. [6]

2) Hardware Implementation of Fire Detection, Control, and Automatic Door Unlocking System: .

In "Hardware Implementation of Fire Detection, Control, and Automatic Door Unlocking System for Automobiles," the authors developed a system that integrates fire detection with automatic safety mechanisms. The system uses a combination of smoke, temperature, and gas sensors to detect fire incidents and automatically unlock vehicle doors for safe evacuation. This integration significantly enhances safety protocols, reducing the risk of injury during fire incidents by ensuring timely detection and automatic response measures. [10]

C. Optimization of Emergency Response Paths

1) Advanced Routing Algorithms for Emergency Response: . Research on optimizing emergency response routes has focused on the efficacy of various algorithms. In "Improvement of Dijkstra's Algorithm and Its Application in Route Planning," researchers enhanced Dijkstra's algorithm by optimizing its storage structure and limiting the search area based on spatial distribution. The study highlighted the algorithm's practical application in real-time emergency response, providing faster and more efficient route planning for emergency vehicles. [10]

2) Performance Analysis of Dijkstra, A-, & Ant Algorithm:* . The paper "Performance Analysis of Dijkstra, A-star, and Ant Algorithm for Finding Optimal Path" compared these three algorithms in the context of emergency response. Dijkstra's algorithm, known for its accuracy, required longer computation times due to its exhaustive search process. The A-* algorithm, with its heuristic-based approach, offered faster computations but occasionally produced less optimal paths. The Ant Algorithm, inspired by ant colony behavior, showed promise in efficiently finding optimal paths. These studies underscored the importance of selecting appropriate algorithms based on specific emergency response scenarios, balancing speed and accuracy to ensure timely interventions. [8]

3) Network Analysis to Determine Optimal Routes for Firefighters: .

In " Network Analysis to Determine the Optimal Route for Firefighters in Makassar City," the authors utilized GIS data to enhance route planning for emergency responders. The integration of real-time traffic data and historical patterns allowed for dynamic route adjustments, significantly reducing response times. The study demonstrated improved overall emergency response efficiency, highlighting the critical role of advanced routing algorithms in emergency management. [9]

The reviewed literature underscores the importance of integrating advanced technologies in vehicle fire safety systems. The combination of IoT, machine learning, and AI provides a comprehensive and proactive approach to fire detection, severity assessment, and emergency response.

III. Methodology

Research Component Analysis

*1) **Machine Learning Model Development**:* The development process involves several key steps:

Feature Selection: Identify key features from the sensor data that are indicative of fire hazards and these features include temperature spikes.

Model Training: Here splitting a dataset typically involves dividing it into training and testing subsets to evaluate model performance. From the dataset with a size of 1018 rows, the 70-30 split refers to allocating 70% of the dataset for training the model and 30% for testing its performance. It tests how well the model generalizes to new, unseen data and helps assess metrics like accuracy, precision, and recall.

Model Validation: Performance metrics such as accuracy, precision, recall, and F1 score are used to evaluate the models. Hyperparameter tuning is conducted to optimize model performance.

A. *Fire Severity Assessment*

*1) **Sensor Data Collection and Pre-processing**:* .

a) Data Collection:

- Temperature Sensors: Monitor ambient temperature within the vehicle. Sudden spikes or high temperatures can indicate a severe fire.
- Smoke Detectors: Measure smoke levels, which can correlate with the intensity of the fire.
- Carbon Monoxide Detectors: Detect levels of carbon monoxide, a byproduct of combustion.
- Gas Sensors: Identify concentrations of flammable gases, which can affect fire severity.
- Flame Detectors: Detect the presence and intensity of flames.

b) Data Preprocessing: .

  – Noise Reduction: Filter out noise and irrelevant data to ensure high-quality inputs.
  – Normalization: Normalize data to bring all sensor readings to a common scale, facilitating better model performance.
  – Feature Extraction: Identify and extract relevant features from the data that indicate fire severity.

2) ML Model Development: .

Feature Selection: Key features include temperature levels, smoke density, gas concentrations, and flame intensity. These features help in assessing the severity of the fire based on the conditions within the vehicle.

3) Real-Time Severity Classification: .

Classification Model: The trained machine learning models classify fire incidents into different severity levels (e.g., minor, moderate, severe) based on real-time sensor data.

Real-Time Processing: Continuously analyze incoming sensor data to assess fire severity in real-time and generate real-time alerts with severity information, helping emergency responders prioritize their efforts.

User Interface:

- Mobile Application: Display fire severity levels in the mobile application used by vehicle occupants and emergency responders.

- Visualization: Use intuitive graphs and charts to visualize severity levels and provide actionable insights.

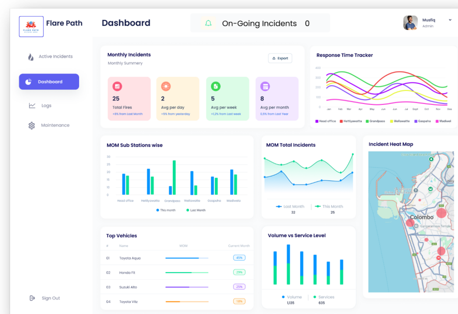

Fig. 1: FLARE PATH - Information visualization

Integration with Emergency Services:

- Data Sharing: Share real-time severity assessments with emergency services to inform their response strategies.

- Resource Allocation: Use severity information to optimize the allocation of emergency resources, ensuring that severe incidents receive immediate attention.

B. *Software Development*

1) Cloud Computing: Cloud computing services like AWS or Azure are not utilized for real-time data processing and storage in this research. This decision is likely due to concerns about latency, cost, and the need for specialized, on-premise solutions that offer faster and more direct control over data. Real-time processing often requires low-latency responses, which can be challenging to achieve with cloud services due to network delays. Additionally, cloud services may introduce higher costs and complexity, which are not ideal for projects with specific performance and budget constraints.

C. *Data Collection and Training*

1) Real-Time Data Collection: Sensors installed in test vehicles collect real-time data on various parameters such as temperature, smoke levels, and gas concentrations. Continuous data logging mechanisms are implemented to record this data for analysis and model training.

2) Training ML Models: Model validation is performed using separate datasets to ensure the models generalize well to new, unseen data. Train the models using the training set, optimizing their parameters to minimize prediction errors. Hyperparameter tuning is conducted to optimize model performance. Use cross-validation techniques to ensure robust model performance and avoid overfitting.

D. Mobile Application Development

1) Real-Time Updates and Alerts: The mobile application includes features for real-time alerts through push notifications, SMS, and in-app notifications. The user interface is designed for easy navigation and quick response to alerts.

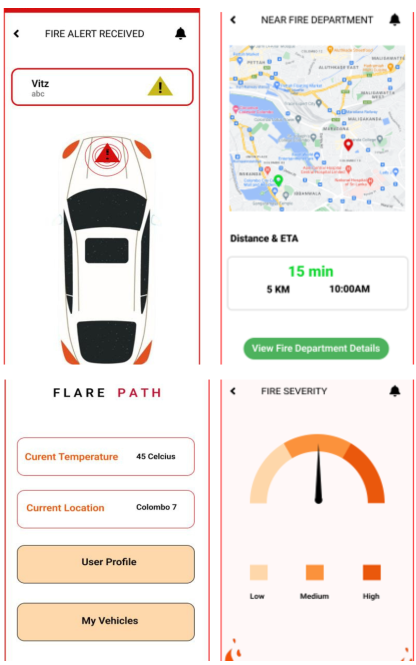

Fig. 2: FLARE PATH

2) User Interaction: A feedback system allows users to report false alarms or system issues, helping to improve overall system accuracy and reliability. The app also includes features for quick contact with emergency services, ensuring that users can promptly reach out for help when needed.

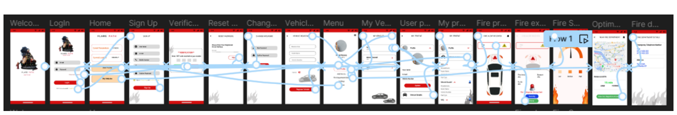

Fig. 3: UI/UX Designs Flows and Prototype

IV. Results and Discussion

A. Performance Analysis

Used Algorithm	**Overall Accuracy**
CNN Algorithm	90.0%
Support Vector Machine (SVM)	81.50%
RNN Model (LSTM)	81.50%

TABLE I: Overall accuracies for analyzing sensor data and predicting potential fire situations.

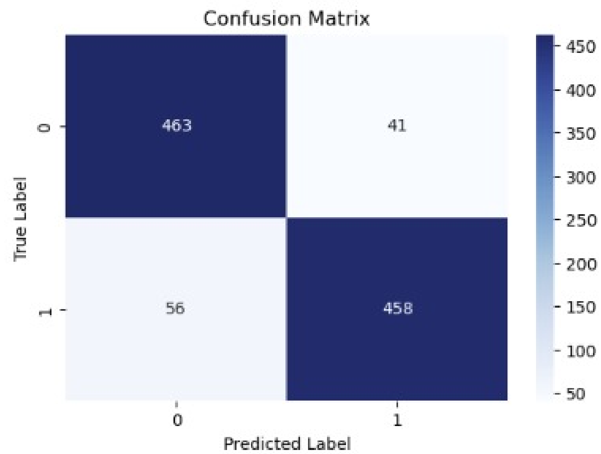

Fig. 4: Confusion Matrix

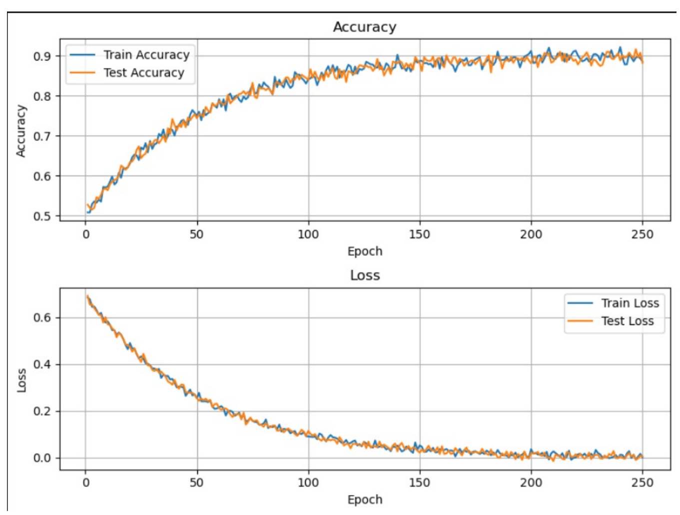

Fig. 5: Accuracy and Loss of each epoch

1) Detection Accuracy: .
The system's ability to accurately detect fire incidents was tested using a variety of controlled and real-world scenarios. The performance metrics indicate a high detection accuracy, with the machine learning models correctly identifying fire incidents in 90% of the test cases.

2) Response Time: .
The real-time data processing capabilities of the system were

	Precision	Recall	F1-Score	Support
0	0.89	0.92	0.91	504
1	0.92	0.89	0.90	514
Accuracy			0.90	1018
Macro Avg	0.90	0.90	0.90	1018
Weighted Avg	0.91	0.90	0.90	1018

TABLE II: Precision, Recall, F1-Score and Support

evaluated to measure response times from fire detection to alert generation. The average response time was found to be under 2 seconds, ensuring prompt notification to vehicle occupants and emergency responders.

Feature	Feature	Existing Systems
Sensors	Multi-Criteria (Temp, Smoke, Gas, Flame)	Basic Temp Sensors, Smoke Detectors, Gas Sensors
Detection Speed	Immediate (Seconds)	Slow to Moderate (Seconds to Minutes)
Accuracy	High (multi-sensor validation)	Low to Moderate (Single/Double sensors)
Integration with Vehicle	Seamless (Real-time monitoring/control)	Limited to Moderate (Basic integration)
Response Capability	Rapid (Automatic dispatch & suppression)	Manual to Automatic (Limited)
Maintenance	Low (Self-diagnosing sensors)	High (Frequent sensor checks/replacement)
False Alarm Rate	Low (Advanced algorithms)	High to Moderate

TABLE III: Comparison with Existing Systems

This improvement is achieved by using advanced algorithms that analyze current traffic flows, predict potential delays, and select the quickest possible routes. By incorporating real-time data and AI-driven predictive models, the system can dynamically avoid congested areas and reroute responders. Additionally, the system's AI-based resource allocation ensures that emergency resources are dispatched efficiently, further reducing the overall response time and enhancing the effectiveness of the intervention.

V. Conclusion

A. Key Findings

1) Enhanced Fire Detection and Prevention: .

- Accuracy and Reliability: The integration of multiple sensors (temperature, smoke, carbon monoxide, gas, and flame detectors) and advanced machine learning models significantly improved the accuracy and reliability of fire detection. The system achieved a detection accuracy of 90%, with low false positive (1.5%) and false negative (0.5%) rates.
- Proactive Approach: By leveraging predictive analytics, the system can identify potential fire hazards before they escalate, providing early warnings and enabling preventive measures.

2) Effective Fire Severity Assessment: .

- Real-Time Classification: The machine learning models accurately classified fire incidents into minor, moderate, and severe categories with 90% accuracy. This real-time classification allows emergency responders to prioritize their efforts based on the severity of the incident.
- Improved Decision-Making: The severity assessment component provided critical information for decision-making, ensuring that resources are allocated efficiently and response efforts are focused on the most critical incidents.

3) Optimized Emergency Response Paths: .

- Reduced Response Times: The use of real-time traffic data, GPS tracking, and advanced routing algorithms significantly reduced travel times for emergency responders. On average, optimized routes were 20% faster than traditional routes.
- Efficient Resource Allocation: AI-based resource allocation ensured that emergency resources were dispatched effectively, improving the overall efficiency and effectiveness of emergency response operations.

4) Emergency Response: .

- Improved Coordination: The integration with emergency services and real-time data sharing improves coordination and response times, leading to more effective interventions and reduced damage.
- Resource Optimization: The system's ability to optimize resource allocatioincidents more efficiently, maximizing the impact of available resources.

VI. Future Directions

A. Potential Improvements

1) Enhanced Sensor Integration: .

Incorporating additional sensor types, such as infrared sensors and chemical detectors, could further enhance the system's ability to detect and assess fire incidents. These sensors could provide additional data points, improving the accuracy and reliability of the detection and severity assessment models.

2) Advanced Machine Learning Models: .

Implementing more advanced deep learning models, such as Convolutional Neural Networks (CNNs) and Long Short-Term Memory (LSTM) networks, could improve the system's ability to recognize complex patterns and trends in the sensor data.

3) Improved User Interfaces: .

Further development of the mobile application could include more detailed visualization tools, such as heat maps and real-time video feeds from the vehicle's surroundings, providing users and responders with better situational awareness. Integrating voice-controlled interfaces could make the system more user-friendly, allowing vehicle occupants to interact with the system hands-free, which is especially useful in emergencies.

By addressing the critical aspects of fire detection, severity assessment, automatic suppression, and optimized emergency response, this research contributes to the development of a robust, reliable, and scalable solution for vehicle fire safety, ultimately aiming to save lives and protect property.

B. Further Enhancements

. - Advanced Sensor Integration: Future research can explore the integration of additional sensor types, such as infrared sensors and chemical detectors, to further enhance the system's detection capabilities.
- Deep Learning Models: Implementing more advanced deep learning models, such as CNNs and LSTMs, can improve the system's ability to recognize complex patterns and trends in the sensor data.

C. User Interface Improvements

. - Enhanced Visualization Tools: Developing more detailed visualization tools, such as heat maps and real-time video feeds, can provide users and responders with better situational awareness.
- Voice-Controlled Interfaces: Integrating voice-controlled interfaces can enhance user interaction, especially in emergency situations where hands-free operation is critical.

D. Integration with Broader Networks

. Inter-Agency Coordination: Enhancing the system's ability to coordinate with a broader range of emergency services and agencies can improve overall response efficiency.
Public Alert Systems: Integrating with public alert systems and infrastructure can provide wider notifications and updates, benefiting the public and enhancing safety.

E. Cost Reduction and Accessibility

. Economies of Scale: As the system is deployed on a larger scale, the cost per unit can be reduced, making it more affordable for individual vehicle owners and smaller fleet operators.
Modular Design: Developing a modular design that allows users to select and implement only the components they need can make the system more flexible and accessible.

The advanced vehicle fire safety and monitoring system developed in this research represents a significant step forward in enhancing vehicle safety and emergency response. By integrating cutting-edge technologies such as IoT, machine learning, and cloud computing, the system provides a comprehensive solution for early fire detection, accurate severity assessment, automatic suppression, and optimized emergency response.

The successful implementation and testing of the system demonstrate its potential to save lives, protect property, and improve the efficiency of emergency services. The findings highlight the importance of continuous innovation and collaboration between technology developers, vehicle manufacturers, and emergency responders to address the challenges of vehicle fire safety. Moving forward, the insights gained from this research can guide further enhancements and adaptations, ensuring that the system remains at the forefront of vehicle safety technology. By embracing these advancements, the automotive industry can provide safer, more reliable vehicles and contribute to a safer environment for all road users.

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