Integrated Smart Vehicle Fire Detection and Suppression System for Enhanced Passenger Safety

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Abstract-*Vehicle fire incidents continue to pose a significant risk to human safety and property. Conventional vehicle fire protection methods mainly depend on manual intervention, which may delay response during emergency conditions. This paper presents an automated vehicle fire detection and suppression system intended to reduce fire escalation at an early stage. The proposed system integrates a microcontroller-based control unit with multiple sensing elements temperature, smoke, and flame sensors to improve detection reliability through multi-sensor confirmation logic. Once a fire condition is validated, the system activates a fire suppression module, isolates selected electrical loads, unlocks vehicle doors, and transmits an emergency alert with location information through a GSM/GPS communication module. A conditional window ventilation strategy is proposed as an additional safety feature. The architecture is applicable to both internal combustion engine vehicles and electric vehicles with suitable sensor and nozzle placement. Prototype-level evaluation indicates rapid detection and response performance, demonstrating the potential of the system as a cost-effective enhancement to vehicle safety.*

Key Words: Vehicle fire safety, automatic fire suppression, multi-sensor detection, GSM alert, automotive safety, electric vehicle fire protection.

1. INTRODUCTION

Vehicle fires remain a critical safety concern despite advances in automotive engineering. Common causes include electrical short circuits, overheating, fuel leakage, mechanical failures, and battery-related faults in electric vehicles [1][2]. Once ignition occurs, the confined geometry of a vehicle and the presence of combustible materials can accelerate flame spread and smoke accumulation [3].

Traditional fire extinguishers require manual operation and depend on driver awareness, accessibility, and reaction time. In severe cases, electrical failures may also affect door locking systems and communication functions. These limitations create a need for automated systems capable of detecting fire conditions and initiating immediate protective actions [4], [5].
This paper proposes a practical automated vehicle fire extinguisher system that combines early fire detection, suppression, electrical isolation, door unlocking, and remote emergency notification in a single integrated platform.

2. LITERATURE REVIEW

Several studies have investigated fire safety systems for automobiles. Sensor-based vehicle fire detection platforms using temperature and gas sensors have been proposed for early warning applications [6][7]. IoT-enabled systems using GSM and GPS modules have been developed to transmit emergency alerts and location data [8]. Real-time fire and smoke monitoring frameworks combining sensor arrays with automated safety responses have similarly been demonstrated for passenger vehicles [11].

Other studies have focused on automatic suppression mechanisms, including extinguisher actuation modules and relay-controlled shutdown systems [2][9]. In electric vehicles, increasing attention has been given to battery thermal runaway detection and cooling-based mitigation strategies [1]. Cost-effective automatic extinguishing architectures targeting EV battery fires triggered on combined flame/smoke sensing have also been reported [10].

Although prior research has demonstrated individual functions such as detection, alerting, or suppression, fewer systems integrate these into a unified low-cost architecture. The present work addresses this gap through a coordinated multi-sensor control approach.

Table -I: Comparison of Related Work and Identified Gaps

Reference	Core Method	Key Limitation
Kiruthika et al. [2]	Single sensor + valve, door unlock, battery disconnect	No multi-sensor confirmation; no cabin ventilation
Yuvaraj et al. [4]	Flame/temp/smoke sensing, automatic door opening	No suppression actuation or GSM/GPS alerting
Nonda et al. [9]	IoT-based suppression with GSM alert and speed monitoring	No load isolation or door/window safety response

Kulkarni et al. [10]	EV extinguisher on flame/smoke	Single-class focus; no cabin ventilation or alerting
Joy et al. [11]	Real-time sensor-array monitoring with safety response	Suppression actuation not primary focus
Proposed System	Multi-sensor, suppression, load isolation, door unlock, window, GSM/GPS	Unified architecture; prototype-stage only

3. SYSTEM REQUIREMENTS AND DESIGN OBJECTIVES

Vehicle fires may progress rapidly from a localized fault to a major hazard within a short time. Delays in detection or response increase damage to the vehicle and surrounding property. Manual extinguishing methods may not always be practical during emergencies. The proposed system is therefore designed to fulfill the following objectives:

A. Detect fire conditions quickly and reliably
B. Reduce false alarms caused by isolated sensor anomalies
C. Activate suppression automatically without human input
D. Isolate selected electrical sources to prevent secondary ignition
E. Unlock vehicle doors for rapid passenger egress
F. Roll down windows to improve cabin ventilation (stationary only)
G. Notify emergency contacts with vehicle GPS location

4. VEHICLE FIRE DEVELOPMENT STAGES

A vehicle fire typically begins as a localized event before developing into a hazard affecting the entire vehicle. Ignition generally starts within the engine bay, triggered by a fuel leak contacting a hot surface or by an electrical fault such as a short circuit or damaged wiring insulation [13]. At this stage the flame is small and confined, but if left unaddressed it begins to spread along nearby combustible materials including wiring harnesses, hoses, and trim components.

As combustion continues, visible smoke starts escaping through gaps around the hood. Continued heat exposure begins to affect nearby components: tires can soften, deform, or burst under elevated temperature, and glass surfaces may crack once thermal stress exceeds structural limits [13].

Once structural barriers are compromised, the fire gains new pathways into the passenger cabin. Heat and flame travel faster along the upper sections of the vehicle body due to convective upward flow. If the fire reaches the cabin, smoke density increases sharply, reducing visibility and breathable air. This staged progression is the basis for the detection and response timeline targeted by the proposed system.

Table -II: Stages of Vehicle Fire Development and Associated Events [13]

Stage	Fire Event Description
Initial Ignition	Fire originates in engine bay due to fuel or electrical fault
Early Flame Spread	Flames emerge from engine openings and cracks
Smoke Generation	Dense smoke begins to emit from vehicle hood
Component Failure	Tires and nearby components degrade due to heat
Fire Growth	Fire intensifies and spreads toward passenger cabin
Cabin Involvement	Passenger compartment becomes engulfed in flames
Fire Propagation	Fire spreads to adjacent vehicle or surroundings

5. PROPOSED SYSTEM ARCHITECTURE

The proposed system consists of three functional units. Sensors are installed in critical zones including the engine compartment, battery area, and passenger cabin. Fig. 2 presents the system architecture block diagram illustrating the interconnection between the sensing, control, and execution units.

Sensing Unit

A. Temperature sensors for heat rise detection
B. Smoke/gas sensors for combustion by-products
C. Flame sensors for direct flame radiation detection

Control Unit

A microcontroller processes sensor signals continuously. Detection logic compares measured values against predefined thresholds and validates fire conditions using multi-sensor confirmation rules.

Execution and Alert Unit

Upon confirmation of fire conditions, the control unit performs the following actions simultaneously:

A. Activates the fire extinguisher module
B. Disconnects selected electrical loads through relays
C. Unlocks vehicle doors for passenger egress

D. Rolls down windows (stationary condition only)
E. Sends emergency alerts via GSM/GPS communication

6. SYSTEM COMPONENTS

A. Sensor Selection and Justification

Temperature Sensor: LM35-type sensors identify abnormal heat rise in engine or battery zones. Automotive-grade NTC/PT100 sensors are recommended for production deployment.

Smoke/Gas Sensor: MQ-2 sensors provide early warning during smoldering or incomplete combustion stages and are suitable for prototype validation.

Flame Sensor: IR or UV-based flame sensors detect direct flame radiation and provide rapid confirmation during ignition events.

Multi-Sensor Strategy: Fire conditions are validated only when at least two sensing indicators exceed critical limits within a defined time window, consistent with multi-signature alarm algorithms shown to reduce nuisance alarms in controlled testing [15].

Table -III: Sensor Comparison for Prototype and Deployment

Parameter	Prototype	Automotive	Remarks
Temperature Sensor	LM35	Automotive NTC/PT100	Heat rise
Flame Sensor	IR Flame Module	UV-IR Dual Spectrum	Fast flame detection
Smoke/Gas Sensor	MQ-2	Electrochemical Gas	Early warning

Fig. 1: MQ-2 Smoke Sensor, LM35 Temperature Sensor, and IR Flame Sensor

B. Microcontroller

Arduino Uno is used as the central control unit for processing sensor inputs and controlling suppression and safety actuators. It interfaces with relay modules, motor drivers, the GSM/GPS module, and the alarm system through its digital and analog I/O pins.

C. Fire Extinguisher Module

The Fire Extinguisher Module is a mechanical-electrical actuation system designed to automatically discharge a fire extinguishing agent when a fire is detected. This module is controlled by the microcontroller without human intervention. Fabrication-level studies support the feasibility of relay-actuated extinguisher modules for vehicular use [12].

D. Motor Driver

The Motor Driver Module is an interface circuit used to control DC or gear motors through the microcontroller. Since the Arduino cannot supply sufficient current to drive motors directly, the motor driver acts as a power amplifier for window and door actuators.

7. SAFETY MECHANISMS

A. Door Unlock Control-Upon fire detection, the microcontroller activates a relay that triggers the vehicle's central locking system to unlock all doors automatically, ensuring immediate passenger evacuation.
B. Window Roll-Down-Upon confirmed fire detection and cabin smoke presence, the microcontroller partially lowers the power windows under stationary conditions, reducing smoke accumulation and improving visibility for occupants.
C. GSM Alert System-The GSM module sends real-time emergency notifications containing vehicle GPS coordinates to predefined contacts including vehicle owners, emergency services, or fleet management systems.
D. Alarm Buzzer-An audible alarm buzzer and status LEDs provide warning signals indicating normal operation, alert, or confirmed fire detection states.
E. Automatic Fire Suppression-The microcontroller triggers the extinguisher module, which releases the extinguishing agent through strategically placed nozzles in high-risk areas such as the engine compartment.

8. METHODOLOGY

The system operates in a continuous monitoring loop. Sensor data are sampled periodically by the microcontroller. Threshold comparison and rate-of-rise logic are applied to temperature signals, while smoke concentration and flame detection outputs are evaluated simultaneously. The operational flowchart is presented in Fig. 3.

A fire event is confirmed when at least two independent indicators are present:

A. High temperature + smoke detection
B. Flame detection + smoke detection

C. Rapid temperature rise + flame detection

After confirmation, relay modules disconnect selected electrical circuits to reduce secondary ignition risks. Door locks are released and windows may be lowered if the vehicle is stationary. The communication module then transmits an emergency message with GPS coordinates to predefined contacts.

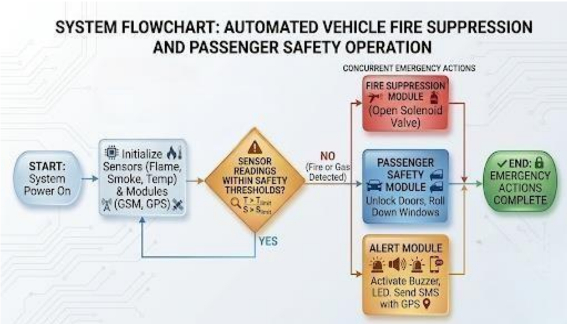

Fig. 3: System Flowchart - Automated Vehicle Fire Suppression and Passenger Safety Operation

9. RESULTS AND DISCUSSION

Prototype testing was conducted using an Arduino Uno, an LM35 temperature sensor, an MQ-2 smoke/gas sensor, and an IR flame sensor module, with relay-driven outputs representing the suppression valve, door lock, and window motor circuits. Heat, smoke, and flame conditions were introduced individually and in combination using controlled artificial sources under indoor ambient conditions. Each test condition was repeated five times and results represent the average of those trials.

Table -IV: Typical Prototype Response Time

Test Condition	Detection Time	Trigger Time	Total Response
Temperature Rise	3.2 s	1.4 s	4.6 s
Smoke Generation	2.8 s	1.5 s	4.3 s
Flame Exposure	1.6 s	1.2 s	2.8 s

The flame sensor produced the fastest confirmation response at 2.8 s total, while temperature rise produced the slowest at 4.6 s. Multi-sensor confirmation reduced unintended triggering during isolated heat or environmental smoke conditions. Fig. 4 illustrates the comparison of detection, action trigger, and total response times across all three test conditions.

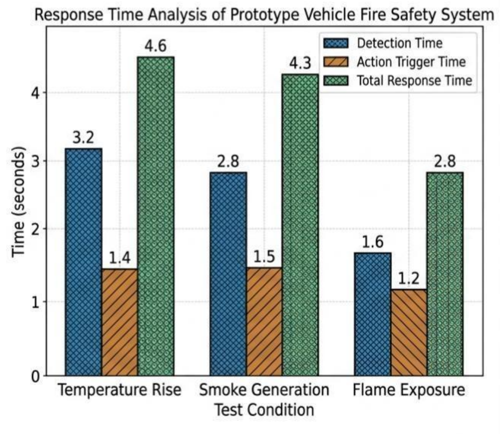

Fig. 4: Response Time Analysis of Prototype Vehicle Fire Safety System

For internal combustion vehicles, suppression nozzles can be directed toward engine and fuel-system zones. For electric vehicles, emphasis may be placed on battery enclosure monitoring and localized suppression support, an area where gas- and aerosol-based sensing for early thermal runaway detection has shown strong early-warning performance [14].

10. ADVANTAGES AND APPLICATIONS

Advantages

A. Early automated fire response without human intervention
B. Improved detection reliability through multi-sensor fusion
C. Remote alert capability with GPS location transmission
D. Adaptable to multiple vehicle types including EVs
E. Scalable, low-cost architecture suitable for mass deployment

Applications

A. Passenger and commercial vehicles
B. Electric and hybrid vehicles
C. Public transport buses
D. Industrial, military, and autonomous vehicles

11. FUTURE SCOPE

Future improvements may include:

A. Thermal runaway prediction for EV battery packs using gas off-gassing and voltage signatures
B. Integration with the vehicle CAN bus for direct access to engine and battery telemetry
C. Automatic eCall-style emergency initiation in parallel with GSM/GPS alerting
D. Fire localization algorithms to identify the specific zone of origin within the vehicle

E. Camera-based fire detection as a supplementary confirmation channel
F. Cloud-based fleet monitoring for commercial and public transport applications
G. Machine learning models trained on multi-sensor data to further reduce false alarm rates
H. Automotive-grade, vibration- and temperature-rated sensor modules for deployment readiness.

12. CONCLUSION

This paper presented an automated vehicle fire extinguisher system designed to improve fire response capability in modern vehicles. By combining temperature, smoke, and flame sensing with multi-sensor validation logic, the proposed system provides reliable detection while reducing false alarms. Automatic suppression, electrical isolation, door unlocking, a conditional window ventilation strategy, and remote emergency alerts collectively enhance overall safety response. Prototype-level evaluation demonstrates promising performance with total response times ranging from 2.8 s to 4.6 s across all three test conditions, supporting further development toward practical automotive implementation.

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