Using Machine Learning to Improve Fuel Safety Monitoring and Compliances

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ABSTRACT
The SafeFuel Monitor is an innovative real-time hydrotesting compliance alert system designed to enhance safety and improve regulatory compliance in the transportation and storage of hazardous fluids, particularly in the petroleum and chemical industries. This paper outlines the importance of hydrotesting, the gaps in traditional compliance monitoring methods, and how the SafeFuel Monitor leverages modern technology, including IoT sensors and machine learning algorithms, to provide timely alerts that enhance operational safety and regulatory adherence.

General Terms
Hydrotesting, Real-Time Monitoring Safety Compliance, IoT (Internet of Things), Data Analytics, Machine Learning, Predictive Maintenance, Regulatory Adherence, Energy Safety Systems, Pipeline Monitoring, Environmental Safety, Automation, System Architecture, Visual Analytics, Compliance Alerts, Smart Systems

Keywords
Accident Safety CNG Cylinder Hydrotesting SafeFuel·vehicle

1. INTRODUCTION
Hydrostatic testing (or hydrotesting) is a critical process used to ensure the integrity and safety of pipelines, tanks, and vessels that transport or store hazardous materials. It involves filling the vessel with water (or another incompressible liquid) and subjecting it to pressure to identify leaks and verify the structural integrity of the system. Regulatory agencies require regular hydrotesting to ensure that these systems can safely contain hazardous materials. However, traditional compliance monitoring methods often lack real-time capabilities, leading to potential safety risks and regulatory non-compliance. Hydrotesting is a crucial procedure for ensuring the integrity and safety of fuel tanks and pipelines [8]. Traditional methods of hydrotesting involve scheduled, manual inspections, which can lead to delays and potential compliance issues. This paper introduces SafeFuel Monitor, a real-time compliance alert system designed to automate and enhance hydrotesting processes. The system leverages sensors, data analytics, and real-time alerts to ensure that fuel storage and transport infrastructure meet safety standards continuously. This paper outlines the system's architecture, functionality, and potential impact on industry practices [1].

2. EASE OF USE
CNG as a fuel
Compressed Natural Gas (CNG), used in natural gas vehicles (NGVs), is essentially the same natural gas supplied to homes for heating and cooking purposes. The production of CNG involves compressing natural gas, primarily composed of methane (CH_4), to less than 1% of its original volume at standard atmospheric pressure. This compressed gas is stored in sturdy, cylindrical containers that can withstand pressures between 20 and 25 MPa (3000 to 3600 psi). While the energy density of CNG at these pressures is lower than gasoline, it retains approximately 27 to 33% of the energy found in gasoline per unit volume. The comparison of the physical and chemical properties of CNG with diesel and gasoline is shown in Table 1 [4].

Table 1 Physiochemical properties of CNG versus gasoline and diesel [5]

Properties	CNG	Gasoline	Diesel
Octane/cetane number	120–130	85–95	45–55
Molar mass (kg/mol)	17.3	109	204
Stoichiometric $(A/F)_s$ mass	17.2	14.7	14.6
Stoichiometric mixture density (kg/m^3)	1.25	1.42	1.46
LHV (MJ/kg)	47.5	43.5	42.7
LHV of stoichiometric mixture (MJ/kg)	2.62	2.85	2.75
Combustion energy (MJ/m^3)	24.6	42.7	36
Flammability limit in air (vol % in air)	4.3–15.2	1.4–7.6	1–6
Flame propagation speed (m/s)	0.41	0.5	–
Adiabatic flame temp. °C	1810	2150	2054
Auto-ignition temp. °C	540	258	316
Wobbe index (MJ/m^3)	51–58	–	–

Safety and Environmental Concerns
Incidents involving leaks or ruptures in hazardous material systems can lead to catastrophic consequences, including environmental disasters and loss of life. For instance, spills from pipelines or storage tanks can contaminate soil and groundwater, affecting public health and ecosystems. Hydrotesting serves as a preventive measure to mitigate these risks by identifying

weaknesses before failures occur [2].

3. HAZARDS AND SAFETY STRATEGIES OF NGVS

Compressed Natural Gas Vehicles (NGVs) carry significant mechanical and chemical energy within their gas cylinders. For instance, a 130-liter tank at 200 bars can release energy comparable to about 1.85 kg of TNT (8.7 MJ) if it bursts. The primary hazard is high-speed projectiles from such explosions, which can cause severe injuries, fatalities, and property damage. Additionally, shockwaves from these explosions can be hazardous. Fires on NGVs can stem from both internal and external causes [11]. Internal factors include electrical faults, overheating of bus components, or combustible materials like polymers, oils, and dust within the engine compartment. External factors may involve maintenance errors, such as using open flames, vandalism, or fires spreading from nearby vehicles or infrastructure. To mitigate the risks of tank bursts and fires, CNG cylinders are equipped with various protective devices [4].

Abbreviations and Acronyms

• **API**: American Petroleum Institute
• **CUI**: Corrosion Under Insulation
• **HC**: Hydrocarbon
• **HSE**: Health, Safety, and Environment
• **ISO**: International Organization for Standardization
• **MTBF**: Mean Time Between Failures
• **MTTR**: Mean Time to Repair
• **NDT**: Non-Destructive Testing
• **P&ID**: Piping and Instrumentation Diagram
• **PLC**: Programmable Logic Controller
• **PSI**: Pounds per Square Inch
• **RTM**: Real-Time Monitoring
• **SCADA**: Supervisory Control and Data Acquisition
• **Sox**: Sulphur Oxides
• **SPM**: Standard Performance Measurement
• **STP**: Standard Temperature and Pressure

Regulatory Landscape

Regulatory bodies such as the Pipeline and Hazardous Materials Safety Administration (PHMSA) in the U.S. and similar organizations globally enforce rigorous standards for scheduled hydrostatic testing of CNG tanks [9]. Adhering to these regulations is essential for ensuring safety and maintaining confidence among stakeholders, including the public, investors, and regulatory authorities. CNG tanks are generally equipped with automatic pressure relief devices (PRDs) or relief valves that are sensitive to pressure and temperature changes [10]. PRDs are vital for the CNG fuel system as they are designed to open and allow the tank to release pressure before reaching a critical failure point or during a fire, preventing potential explosions. These devices are calibrated to melt at approximately 383 K (110 °C), ensuring they activate under high-temperature conditions. PRDs are strategically placed without thermal shielding to effectively react to temperature fluctuations and are directed to minimize harm to nearby vehicles and pedestrians. During a fire, if the gas is released, it exits the tank in controlled jets, similar to the flame of a Bunsen burner, allowing for gradual pressure release and reducing the risk of an explosion [3].

Limitations of Traditional Hydrotesting Practices

Traditional hydrotesting practices often involve manual scheduling, execution, and reporting, which can lead to several issues:

- **Delayed Reporting**: Results may take time to analyse, leading to delayed compliance notifications.
- **Human Error**: Manual data entry and analysis are prone to mistakes, potentially overlooking critical issues.
- **Lack of Real-Time Monitoring**: Traditional methods do not provide continuous monitoring, which means potential issues between scheduled test intervals may go undetected [1].

4. SAFEFUEL MONITOR: CONCEPT OVERVIEW

The SafeFuel Monitor overcomes these challenges by implementing a real-time hydrotesting compliance alert system that leverages cutting-edge technologies, including Internet of Things (IoT) sensors, data analytics, and machine learning.

System Architecture

1. **IoT Sensors**: Smart sensors are installed at critical points in the pipeline or storage facility to continuously monitor pressure, temperature, and other relevant parameters.
2. **Data Collection and Transmission**: Sensor data is continuously transmitted to a central monitoring system through secure wireless networks in real-time.
3. **Data Analysis**: Machine learning algorithms analyse the incoming data to identify patterns, anomalies, and compliance lapses. This analysis also includes historical data to improve predictive capabilities.
4. **Alerts and Notifications**: The system generates real-time alerts for operators and compliance officers in the event of deviations from established safety parameters [3].

Features and Benefits

- **Real-Time Monitoring**: Continuous observation of pressure and temperature parameters ensures that any anomalies are immediately detected.
- **Automated Compliance Alerts**: Automated notifications ensure that compliance officers are alerted to potential issues in real time, enabling prompt action.
- **Data Analytics**: Historical analysis allows for trend detection and identification of potential future failures.
- **Reduced Operational Costs**: By preventing leaks and failures, companies can save significantly on emergency response costs, environmental remediation, and regulatory fines [2].

IMPLEMENTATION AND CHALLENGES

Implementation Strategy

Successful implementation of the SafeFuel Monitor involves several key steps:

1. **Pilot Testing**: Initial deployment in a controlled environment to test system functionality and collect feedback.
2. **Integration with Existing Systems**: Seamless integration with existing monitoring and compliance systems to enhance usability and efficiency.
3. **Training**: Comprehensive training programs for operational staff to effectively use the system [1].

Challenges

1. **Sensor Calibration**: Ensuring sensors are properly calibrated and maintained to avoid false positives/negatives.
2. **Cybersecurity**: Protecting the system from cyber threats is paramount, given the sensitive nature of the data being monitored.
3. **Regulatory Acceptance**: Gaining acceptance from regulatory bodies for the adoption of new technologies in traditional industries [1].

5. WORLDWIDE SAFETY REGULATIONS FOR CNG VEHICLES

Worldwide, safety regulations and design standards are in place to ensure the secure operation of CNG (Compressed Natural Gas) vehicles. These regulations apply to various components within the CNG fuel system, including gas cylinders, valves, fuel lines, pressure regulators, filling connections, gas-air mixers, and electrical systems.

For example, in Europe, compliance with UN-ECE Regulation R-110 is mandatory for CNG vehicle safety, particularly in securing Whole Vehicle Type Approval

(WVTA) as per European Directive 2007/46/EC. Additionally, many European countries implement ISO 11439 for designing safe CNG system components. In the U.S., safety standards like FMVSS 303 and 304 govern the integrity of CNG fuel systems, supplemented by voluntary standards such as NFPA-52 and ANSI NGV3.1-2014, which define guidelines for CNG vehicle fuel containers.

Similarly, Canada enforces the Canadian Motor Vehicle Safety Standards (CMVSS) 301.2, which require manufacturers to demonstrate compliance either through crash test data or adherence to CSA B109 standards. In India, Central Motor Vehicle Rule 115-B, along with Automotive Industry Standards AIS-024 and AIS-028, governs the approval process for CNG vehicles. Following a landmark Supreme Court ruling in 2002, Delhi transitioned to a fully CNG-fueled public transport system, establishing one of the largest such networks globally. However, between 2002 and 2007, the city experienced several incidents of CNG bus fires, shedding light on technical issues that needed addressing.

India has also developed its own set of regulations for CNG vehicles, particularly in response to environmental and public health concerns. The Central Motor Vehicle Rule 115-B governs the approval process for CNG vehicles in India, and this rule references the Automotive Industry Standards AIS-024 and AIS-028, which provide detailed guidelines for the safety and installation of CNG systems. India's push towards CNG was accelerated by a landmark ruling from the Supreme Court in 2002, which mandated that all public transport vehicles in Delhi be converted from diesel and gasoline to CNG. This decision was driven by the need to reduce air pollution in the city. As a result, Delhi now operates one of the largest CNG-fueled public transport systems in the world.

Overall, the global regulatory framework for CNG vehicles reflects a collective effort to promote the safe adoption of CNG technology. While there are regional variations in the specific standards and regulations, the overarching goal remains the same: to ensure that CNG vehicles are designed, manufactured, and operated in a way that prioritizes safety and minimizes the risks associated with high-pressure gas storage and distribution. As the use of CNG continues to grow, these safety regulations will likely evolve to address new challenges and advancements in technology.

However, the rapid transition to CNG in Delhi was not without challenges. Between 2002 and 2007, there were multiple incidents of CNG bus fires reported in the city. These incidents highlighted several technical issues with the CNG buses, including possible flaws in the design and installation of CNG systems, as well as maintenance and operational challenges. These incidents prompted further scrutiny of the safety standards and led to improvements in both regulatory oversight and the technical specifications of CNG systems to prevent such occurrences in the future [4].

Causes of NGV's accidents in Pakistan

The accidents highlighted in Table [2] can be categorized into two parts:

1. Fire explosion

2. Cylinder explosion [4]

Table 2. Accident Data

S. No.	Date	Accident description	Place	Vehicle	No. of deaths	No of injured	Causes
1	30-Mar-08	Explosion of CNG cylinder	Attock	Pickup	2	3	Explosion took place during refilling at CNG station due to substandard cylinder
2	6-Oct-08	Explosion of CNG cylinder	Peshawar	Car	2	4	Explosion took place during refilling at CNG station due to substandard cylinder
3	7-Jun-09	Explosion of CNG cylinder	Rawalpindi	Car	2	4	Explosion took place during refilling at CNG station due to substandard cylinder
4	14-Dec-09	Explosion of CNG cylinder	Mirpurkhas	Car	4	4	Explosion took place during refilling at CNG station due to substandard cylinder
5	18-Feb-10	Explosion of CNG cylinder	Lodhran	Van	6	15	Gas cylinder installed in the van had crossed the standard age and needed to be checked
6	21-Oct-10	Explosion of CNG cylinder	Swabi	Car	2	2	Explosion took place during refilling at CNG station due to substandard cylinder
7	5-Jan-11	Explosion of CNG cylinder	Lahore	Car	–	4	Explosion took place during refilling at CNG station due to substandard cylinder
8	13-Feb-11	Explosion of CNG cylinder	Near Lahore	Van	3	12	Explosion took place during refilling at CNG station due to substandard cylinder
9	12-Jul-11	Fir explosion in CNG bus	Near Islama-bad	Mini-bus	9	3	Gas leakage from any point of CNG Piping system and caught fire possibly of short circuit
10	18-Nov-12	CNG cylinder explosion	Karachi	Mini-bus	2	4	Due to low-quality cylinder, explosion took place during gas filling at CNG station
11	26-Nov-12	Fir Explosion in CNG Van	Near Manga Mandi	Van	7	4	The fire extended in the van due to lighting cigarette
12	26-Nov-12	CNG cylinder explosion	Mardan	Three wheeler	–	4	Due to low-quality cylinder, explosion took place during gas filling at CNG station
13	11-Dec-12	Explosion of CNG cylinder	Karachi	Car	–	3	Unknown causes
14	21-Dec-12	Fir Explosion in CNG Van	Chichawatni	Van	4	10	Sudden fire explosion took place due to gas leakage
15	9-Jan-13	Explosion of CNG cylinder	Faisalabad	Van	1	4	The van was on its way when its cylinder exploded
16	20-Jan-13	Explosion of CNG cylinder	Nowshehra	Car	1	3	Explosion took place during refilling at CNG

6. METHODOLOGY

Despite the growing adoption of Compressed Natural Gas (CNG) vehicles due to their economic and environmental advantages, there exists a notable gap in the monitoring and enforcement of safety compliance for these vehicles. This gap primarily stems from the lack of a comprehensive real-time monitoring system that can effectively track the condition of critical CNG components, ensure adherence to established safety protocols, and provide timely alerts for maintenance or repairs.

Current practices rely heavily on manual inspections, which are not only time-consuming and inconsistent but also inadequate for providing continuous oversight. As a result, these manual processes leave significant room for safety violations to go unnoticed, thereby increasing the risk of vehicle malfunctions, accidents, and potential harm to passengers and the public [13]. The absence of real-time monitoring exacerbates these issues by failing to offer ongoing scrutiny of vehicle conditions, thereby compromising overall safety and operational efficiency [14].

To address this problem, our research focuses on developing and implementing a real-time monitoring system that enhances the safety and reliability of CNG vehicles by providing continuous, automated oversight and timely notifications for necessary actions [14].

7. PROPOSED METHODOLOGY

This research paper proposes a web-based system to enhance the safety and regulatory compliance of Compressed Natural Gas (CNG) vehicles by integrating Optical Character Recognition (OCR) technology with the Petroleum and Explosives Safety Organization (PESO) database. The system aims to ensure that only vehicles meeting safety standards are authorized to refuel at CNG stations. It employs Intelligent Character Recognition (ICR) for accurate license plate recognition [6], starting with high-resolution image acquisition at refuelling stations. ICR algorithms then process these images to extract text data, which is cross-referenced with the SafeFuel Monitor database to verify vehicle compliance. A web-based user interface provides real-time compliance status, data reporting, and alerts for non-compliant vehicles or system errors. This integration minimizes risks, ensures regulatory adherence, and promotes operational efficiency, ultimately fostering a safer environment for both vehicle operators and the public. Future work will focus on optimizing OCR algorithms for diverse license plate designs and expanding the system's capabilities to include other vehicle types and regulatory databases [7]. Work flow of Proposed Methodology is shown in FIG 1.

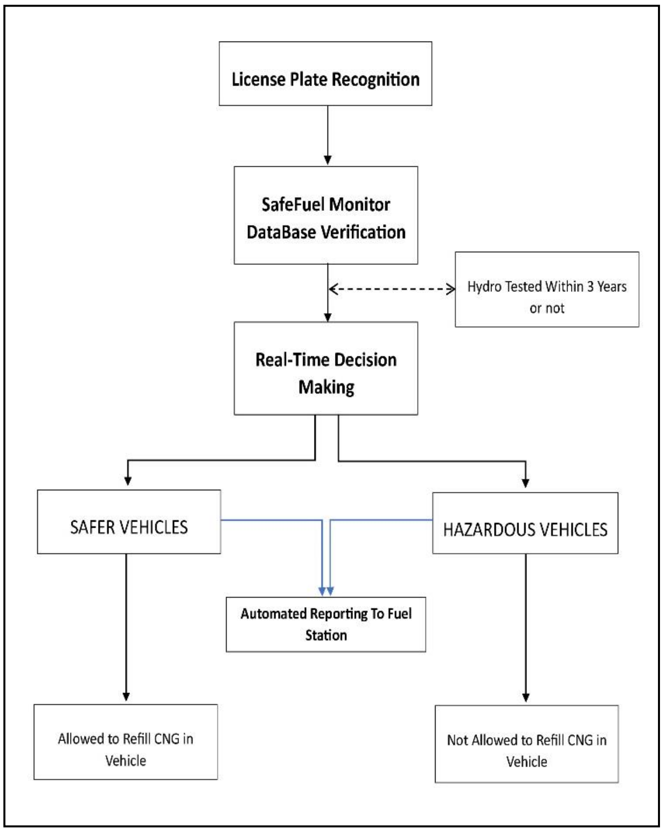

Fig1. Workflow of System

8. DATASET

This research dataset evaluates the compliance of CNG (Compressed Natural Gas) vehicles with mandatory safety regulations, specifically the required hydrotesting of CNG cylinders every three years. It integrates two key data sources: vehicle registration data from the Regional Transport Office (RTO) and hydrotesting certification data from PESO (Petroleum and Explosives Safety Organization) certified dealers. The integration, based on vehicle registration numbers, identifies whether each vehicle's CNG cylinder has undergone hydrotesting within the prescribed timeframe. Key attributes include vehicle details, hydrotesting dates, and certification status. After data cleaning and validation, this dataset supports regulatory compliance monitoring, safety risk assessment, and public safety initiatives. Despite potential limitations like incomplete records or delays in updates, it plays a crucial role in enforcing safety measures for CNG vehicles [15-16]. Structure of data set is shown in FIG 2.

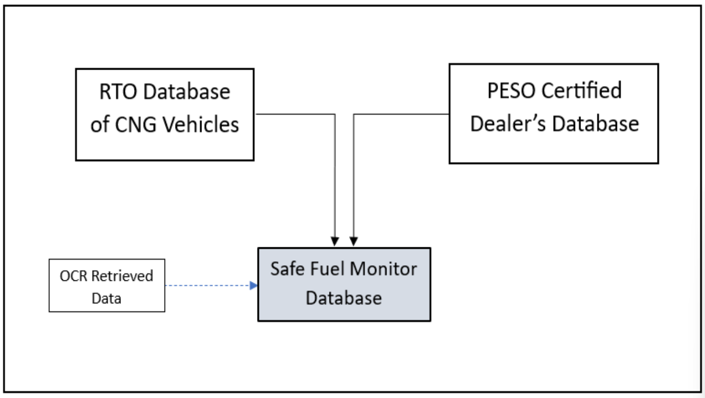

Fig2. Safe Fuel Dataset

9. RESULTS

The table below summarizes the categories of accidents, current incident counts, estimated reductions achieved by the SafeFuel Monitor, and the remaining incidents after implementing the system. Summary of Potential Reduction with comparison in Table 3.

Table 3. Summary of Potential Reduction

Category	**Current Incidents**	**Reduction (75%)**	**Estimated Remaining Incidents**
Explosion During Refueling (25%)	~14	~10.5	~3–4
Non-Compliance with Safety Standards (30%)	~16.5	~12.4	~4–5
Human Error and Manual Oversight (20%)	~11	~8.25	~2–3
Environmental Hazards Due to Leaks (15%)	~8	~6	~2
Operational Downtime and Maintenance Failures (10%)	~5.5	~4.1	~1–2

The data highlights the significant potential of the SafeFuel Monitor to reduce incidents across various categories, achieving up to a 75% reduction in accidents and hazards. Visual representation of Accident vs Potential Reduction with SafeFuel Monitor Fig 2.

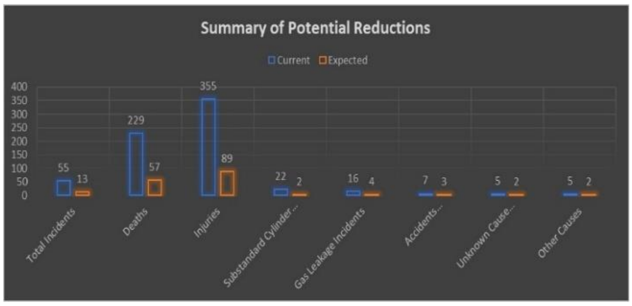

Fig 3. Potential reduction safe fuel

10. CONCLUSION

The SafeFuel Monitor is a game-changing tool designed to improve safety and efficiency in the fuel industry. It offers real-time alerts to help ensure compliance with hydrotesting regulations. Using advanced sensors, a durable design, and an easy-to-use interface, it helps operators reduce risks, cut downtime, and meet regulatory requirements. The monitor provides real-time data, in-depth analytics, and integrated camera features, allowing operators to quickly spot and resolve potential issues, boosting efficiency and lowering costs. Looking ahead, the SafeFuel Monitor has great potential for use in emerging technologies like electric vehicles (EVs), where it could track battery cooling systems and charging infrastructure. It could also be used in ethanol and biofuel-powered vehicles to ensure the safety and quality of alternative fuels. By integrating with IoT platforms and utilizing AI for predictive maintenance, the monitor can create a connected system for centralized monitoring, early issue detection, and better decision-making across operations. With its alignment to global compliance standards and support for emergency response efforts, SafeFuel Monitor is set to transform fuel management systems, contributing to a safer, more sustainable, and efficient future for various industries.

11. FUTURE SCOPE

The versatility of SafeFuel Monitor positions it for expansion into emerging vehicle technologies and fuel systems, unlocking new possibilities for innovation. The system can be adapted for electric vehicles (EVs), where it could monitor battery cooling systems and ensure the safety of charging infrastructure, while its real-time analytics can detect anomalies to enhance operational efficiency. In ethanol or biofuel-powered vehicles, SafeFuel Monitor could ensure fuel safety and quality, aiding in compliance with environmental regulations and optimizing the performance of alternative fuels. By integrating with IoT platforms, the device could enable centralized monitoring, predictive maintenance, and cloud-based analytics across multiple sites, fostering a connected ecosystem for large-scale fuel operations. Leveraging AI and machine learning, the system could evolve into a predictive maintenance tool, identifying patterns of potential failures and reducing downtime. Furthermore, SafeFuel Monitor could be tailored to meet global compliance standards, making it a universal solution for safety and efficiency. Its advanced analytics and visual data capabilities could also play a vital role in emergency response, providing real-time alerts and aiding decision-making during critical situations. As industries transition towards greener and more sustainable practices, SafeFuel Monitor is poised to become a cornerstone of efficient fuel management, paving the way for safer, smarter, and more sustainable systems.

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