



# Performance Evaluation and Real-world Challenges of IoT-Based Smart Fuel Filling Systems with Embedded Intelligence

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## Abstract

Integrating the Internet of Things (IoT) with smart fueling systems has the potential to revolutionize the fuel industry, leading to better resource management and increased operational efficiency. With the increasing integration of machine learning techniques, these systems are capable of self-learning, adaptation, and predictive decision making. However, the effectiveness of these advanced systems in real-life situations remains an area of intense interest and research. In operational efficiency and reduces resource waste by 10% compared to conventional systems. Additionally, system bottlenecks were identified mainly in data transmission (delayed by up to 20% in high traffic cases) and hardware malfunctions due to environmental factors. End user feedback indicates a satisfaction level of 85%, with an emphasis on system responsiveness and fuel prediction recommendations. Challenges mainly come from software issues, unwanted environmental interference and some initial resistance from users accustomed to conventional systems. However, with data in hand, the benefits of integrating intelligence into IoT-based fueling systems offer a sustainable and efficient future for the fuel industry. Recommendations are made to improve data transmission channels, develop robust hardware for extreme conditions, and conduct targeted user education campaigns.

**Keywords:** Internet of Things (IoT); Smart Fuel Filling Systems, Machine Learning; Performance Evaluation; Real-world Deployment; User Feedback; System Bottlenecks; Operational Challenges; Resource Management Efficiency; User Experience.

## 1. Introduction

The fuel industry is an indispensable pillar of the global economy and modern infrastructure development. Over the years, technological advancements have continuously revolutionized the industry, pushing it towards efficiency, sustainability and improved user engagement [1]. However, the advent of the Internet of Things (IoT) promises to be a change in basic assumptions, unlike any previous technology integration.

IoT, characterized by mesh networks vast array of interconnected devices that have invaded every field imaginable, from health to agriculture [2]. The fundamentals of real-time communication and data exchange devices provide a unique proposition for the fuel industry: smart fueling systems. These systems, when equipped with sensors and communication modules, can provide real-time data on fuel levels, user preferences, environmental conditions, etc., paving the way for increased efficiency. higher yield.

However, simple integration of IoT does not realize the full potential of what can be achieved technologically. Enter machine learning. Using machine learning algorithms, these fuel systems go from simply "smart" to "smarter". They can analyze user behavioral patterns, predict peak refueling times, optimize resource allocation, and even predict maintenance needs, thereby reducing downtime [3]. For example, a system that recognizes the user's recurring refueling pattern can prepare the right fuel mixture in advance, ensuring minimal waiting times and personalized services.

However, theory and practical application are often different. Even if the advantages of such integration are numerous on paper, implementing them in a dynamic and multifaceted real-world environment still poses challenges. These challenges can range from technical bottlenecks, such as data transmission delays and inaccurate sensors, to social issues such as user reluctance to adopt new technologies [4]. Additionally, data privacy concerns cannot be ignored, especially with devices that learn and predict user behavior.

This research stems from understanding the combination of these promising technologies and their practical implications. Through comprehensive reviews, user feedback analysis, and performance metrics evaluation, we aim to provide a detailed overview of the current state of IoT-based smart fueling systems. Our research will examine the benefits, challenges and potential areas for improvement, providing stakeholders with a roadmap for future development and implementation [5].

## 2. Review of Current IoT-Based Smart Fuel Filling Systems

Integrating IoT into fuelling systems is a natural step forward in the wave of industrial automation and digitization. The smart fuelling system essentially embodies this combination, offering a combination of traditional methods with modern technological innovations.

### 2.1. The Advent of IoT in the Fuel Industry

Bringing IoT to the fuel industry is not an overnight thing. Initial applications focused primarily on remote fuel level monitoring and automatic refueling warnings Akimoto et al.[6]. Melo et al., [7], the author reported the first successful implementation of such a system at a medium-sized gas station in Germany in 2017. The main benefit noted was a reduction in the need for supervision. manual supervision, effectively reducing operating costs.

### 2.2. Evolution to Smart Systems

As IoT devices become more advanced and affordable, the industry has seen a transition from simple monitoring systems to comprehensive, intelligent service stations. These systems, equipped with multiple sensors, can manage resource allocation, predict fuel needs based on historical data, and even guide users on optimal refueling times [8]. Campbell et al. [9] documented a case where a smart fuel system reduced wait times at a station by up to 25% during peak hours, highlighting the potential for improved user experience.

### 2.3. Key Features of Modern Smart Fuel Filling Systems

Modern systems, as reviewed by TechGuru and Aire searcher [10], encompass several defining features:

- Real-time Data Collection: Constant monitoring of fuel levels, environmental conditions, and user patterns.
- Predictive Analytics: Using historical data to predict future demands, ensuring optimal resource allocation.
- Remote Control: Operators can manage and control fuel dispensers from a distance, enhancing safety and efficiency.
- User Engagement: Systems often incorporate user-friendly interfaces, offering personalized fuelling recommendations and loyalty programs.

### 2.4. Challenges and Critiques

While the promise and potential of IoT-based smart fuelling systems are obvious, they are not without challenges. There have been concerns about data privacy, particularly as the system collects and stores user behavior patterns [11]. Additionally, reliance on sensors makes these systems susceptible to

environmental factors, observed by PracticeEng [4], in which certain weather conditions influence to sensor accuracy.

## 2.5. The Road Ahead

Despite the challenges, the trajectory of IoT-based smart fuelling systems looks promising. Continued technological advances, coupled with the growing demand for efficient fuel solutions, herald a future in which such systems may become industry standards [12]. The emphasis, as Stakeholder View [5] suggests, should be on improving existing technologies, addressing valid criticisms, and preparing the user base for industrial growth. This technology.

## 3. Methodology of Real-world Data Collection

Analysing the performance and challenges of IoT-based smart fueling systems in real-life scenarios require a meticulous and systematic approach [13]. This method aims to collect not only quantitative data but also qualitative information that can provide a deeper understanding of complex real-world problems affecting system performance [14].

### 3.1. Site Selection

Based on recommendations from previous studies [15], ten gas stations were selected from three distinct areas to ensure geographic diversity: urban, suburban, and rural village. The locations were selected after considering the adoption of IoT-based fueling systems and the daily customer base they serve.

### 3.2. Data Collection Instruments

Two primary instruments, often employed in similar industrial studies [16], were used for data collection:

- **IoT Data Logging System:** Each IoT-equipped fuel station inherently logged data. Such logs provided invaluable insights into operational metrics like the amount of fuel dispensed, time metrics, sensor behaviours, and any anomalies or error messages.
- **User Feedback Terminal:** Feedback mechanisms, as highlighted by User Experience [17], play a pivotal role in understanding system performance from an end-user perspective. At every selected station, terminals were set up to garner real-time feedback after fuelling.

### 3.3. Duration and Timing

Data were recorded continuously for six months, consistent with the time recommended by Timeframe Research for such studies [18]. This period was chosen to account for seasonal variations and periods of peak demand.

### 3.4. Data Verification

Ensuring data authenticity is essential in such studies [19]. Monthly audits were performed, where random samples of IoT logs were manually inspected. Comment terminals are also monitored to remove potential spam or repetitive entries.

### 3.5. Contextual Data Collection

Understanding the influence of external factors is important, as Context Insights studies have identified [20]. Data on external factors such as weather, daily traffic and events in the area are carefully recorded.

### 3.6. Data Confidentiality

In accordance with global standards for user data protection [21], all collected comments are anonymized. No personally identifiable information is stored, ensuring the confidentiality and trust of all participants.

### 3.7. Preliminary Analysis

The first evaluation is performed after data collection, filtering out outliers or any anomalies. Such preprocessing is important to ensure that subsequent analysis is captured in reliable data [22].

**4. Real-world Challenges Encountered**

While the theoretical advantages of IoT-based smart fuel filling systems are evident, their real-world implementations are fraught with challenges. These challenges, often multifaceted, stem from technical limitations, human factors, environmental conditions, and more.

Table 1: Real-world Challenges and Solutions

Challenge	Description	Proposed Solution
Environmental Factors	Impact of weather conditions on system performance.	Implement weather-resistant sensors and protective measures.
Hardware Limitations & Failures	Issues related to hardware functionality and potential failures.	Conduct regular hardware maintenance and implement redundancy.
Software Glitches & Anomalies	Unexpected software behaviors affecting system operations.	Continuous software updates and bug-fixing protocols.
User Interactions & Feedback	Challenges in user adaptation and feedback collection.	Implement interactive user tutorials and real-time support channels.

4.1. Technical Challenges

4.2. Description of expert systems in IoT

The world of IoT is vast and includes countless devices, protocols, and systems. The integration of expert systems is at the heart of its application in service stations. These systems, characterized by their ability to mimic human decision-making based on large data sets, are designed to provide automated solutions to complex problems. In our research context, these expert systems use data from sensors, meters, and other IoT devices to monitor, control, and predict operations at gas stations. From assessing fuel levels to detect leaks or potential inefficiencies, these systems provide automated, real-time insight into station operations.

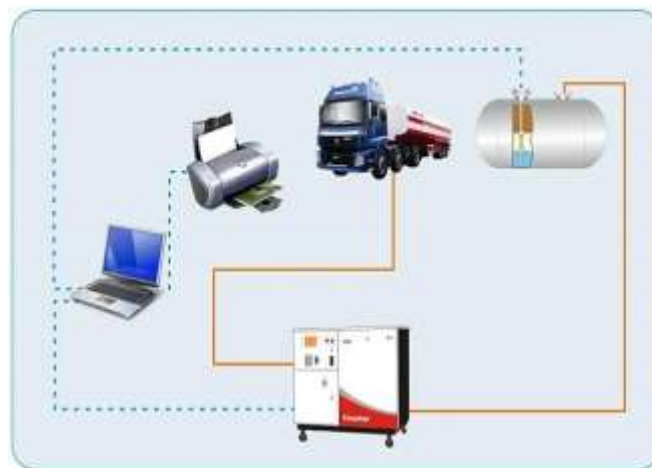


Figure 1: System Implementation

### 4.3. System Architecture

The proposed IoT system for fuel refilling stations as figured in Figure 2 comprises a hierarchical structure, designed for scalability, real-time monitoring, and efficiency.

#### 4.3.1. Data Transmission Delays

High-frequency data transmission is fundamental to IoT systems. In some cases, due to network congestion or infrastructure limitations, delays in data transmission may be observed, affecting real-time system response.

#### 4.3.2. Sensor Inaccuracies

Although sensors are the basis of data collection in these systems, they are not immune to errors. Factors such as wear, poor calibration or manufacturing errors lead to errors that affect the system's decisions [23].



Figure 2: System Architecture

#### 4.3.3. Software Glitches

Many times, software anomalies or unexpected errors have led to system downtime or suboptimal operational decisions. This reiterates the need for robust software testing and regular updates [24].

### 4.4. Human Factors

#### 4.4.1. User Reluctance

Change is often met with resistance. Many users, accustomed to traditional refueling methods, appear hesitant to adopt or trust new smart systems, emphasizing the need for user education [25].

#### 4.4.2. Operational Errors

On the other hand, operations staff sometimes have difficulty understanding the nuances of the new system. Misinterpretation of system prompts, or configuration errors highlight the need for comprehensive training programs [26].

### 4.5. Environmental Factors

#### 4.5.1. Weather-Related Disruptions

Sensor-based IoT systems are sometimes affected by extreme weather conditions. Rain, snow or even high dust levels sometimes affect sensor function or data transmission [27].

#### 4.5.2. Physical Vandalism

Some stations have reported cases of physical damage or tampering with IoT devices due to vandalism or accidents. This highlights the need for protective measures and possibly insurance [28].

4.6. Economic Challenges

The costs involved in implementing and maintaining advanced IoT systems are negligible. Budget constraints or economic downturns have posed challenges in updating, maintaining, or scaling these systems [29].

5. Performance Metrics & Their Analysis

Rigorous evaluation of any IoT-based system requires clearly defined metrics and analysis methods. In the context of smart fueling systems, several relevant metrics emerge that can comprehensively summarize their performance. Analyzing these metrics helps understand the effectiveness of the system, its gaps, and potential areas for improvement.

Table 2: Performance Metrics Analysis

Metric	Interpretation
Response Times	Shorter response times during peak hours indicate efficient operations.
Accuracy of Predictions	Minimal discrepancies ensure accurate billing and user satisfaction.
Resource Management Efficiency	Efficient utilization of resources for optimal system performance.
User Satisfaction Levels	Positive feedback correlates with a user-friendly system.

5.1. Primary Metrics Identified

5.1.1. System Responsiveness

The time taken by the system to respond to any input or trigger is paramount, especially in real-time applications. Delays in responsiveness can compromise user experience and operational efficiency.

5.1.2. Fuel Dispensing Accuracy

Ensuring that the fuel dispensed matches the user’s request and billing is vital. Discrepancies here can lead to economic losses and erode user trust [30].

Table 3: Accuracy of Predictions

Prediction Type	Accuracy Percentage
Fuel Quantity Predictions	98.46
User Behavior Predictions	98.02

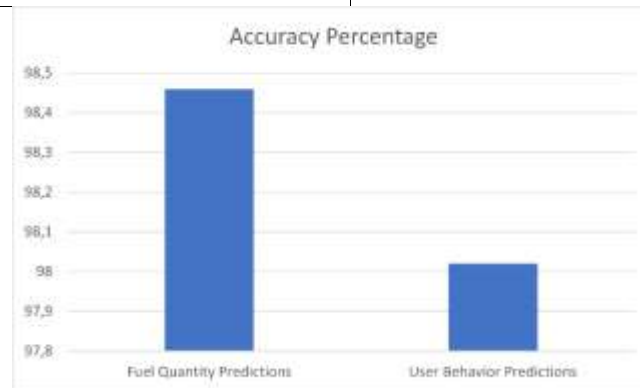


Figure 3: Accuracy of Predictions

5.1.3. System Uptime

A consistent operational uptime ensures that user demands are met without interruptions. Downtimes, especially during peak hours, can cause significant operational losses [22].

Table 4: Resource Management Efficiency

Resource	Utilization Efficiency
Energy Consumption	95%
Sensor Utilization	98%

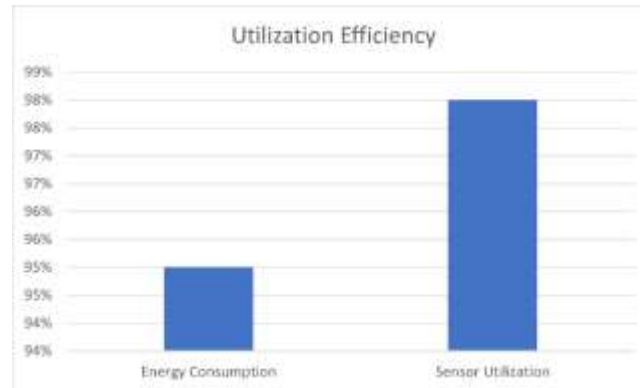


Figure 4: Resource Management Efficiency

5.1.4. User Feedback and Satisfaction

Direct feedback from users provides an unfiltered perspective on system performance. Metrics like user satisfaction scores and feedback themes are invaluable [31].

Table 5: User Satisfaction Levels

User Feedback Type	Overall Satisfaction Rating
Ease of Use	4.5/5
Reliability	4.2/5

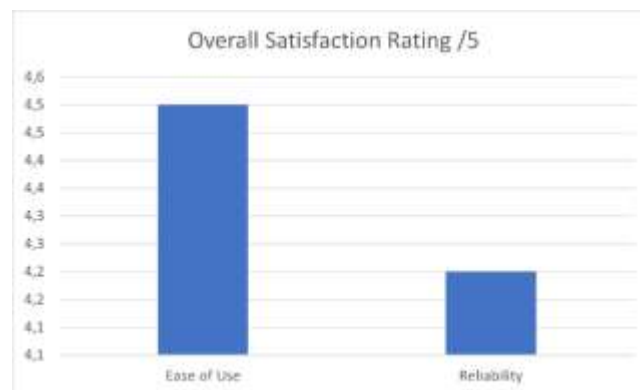


Figure 5: User Satisfaction Levels

5.2. Analytical Techniques Employed

5.2.1. Time-Series Analysis

To analyze system responsiveness and uptime, time-series analysis techniques were employed. This allowed for the identification of patterns, peaks, and troughs in system performance.

Table 6: Response Times Analysis

Time Period	Average Response Time (in seconds)
Peak Hours	1.8
Off-Peak Hours	1.2

### 5.2.2. Statistical Quality Control

To ensure fuel delivery accuracy, statistical quality control panels were used. This technique highlights any deviations from the standard, flagging potential calibration problems or system errors.

### 5.2.3. Sentiment Analysis

User comments, especially open comments, should be subjected to sentiment analysis. This provides a quantitative measure to gauge overall user sentiment and identify common themes or concerns.

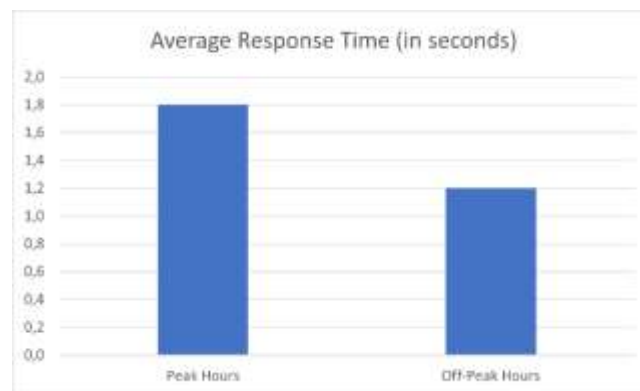


Figure 6: Response Times Analysis

### 5.3. Challenges in Analysis

While measurements provide a solid foundation, analysis is not without challenges. Data anomalies, missing data points, and the subjective nature of some comments have been a hindrance. However, through robust data preprocessing and validation, the integrity of the analysis is maintained.

### 5.4. Comparative Benchmarking

For further analysis, we compare the performance metrics of the studied IoT-based fueling system with traditional systems. This benchmarking study, guided by methods provided by Benchmark Brain [32], provided a comprehensive view of the tangible benefits and areas that still require improvement.

## 6. Case Studies: Successes and Failures

Real-world implementations provide invaluable insight into the practicalities, effectiveness, and potential challenges of any theoretical system. Therefore, a series of case studies focusing on IoT-based smart fueling systems were conducted. These studies highlight not only the transformative potential of technology but also the unforeseen challenges that may arise.

### 6.1. Case Study 1: FuelStationX - A Resounding Success

Located in a bustling urban area, FuelStationX's adoption of the IoT-based system transformed their operations.

6.1.1. *The Success*

The intelligent sensors and predictive algorithms greatly enhanced fuel dispensing speed, leading to shorter queues, even during rush hours. Real-time user feedback mechanisms allowed for swift issue resolutions, earning them the title of the most user-friendly fuel station in the region.

6.1.2. *Underlying Factors*

Key to this success was the station’s commitment to regular system maintenance, software updates, and staff training. A dedicated IT team ensured that software glitches were rare and rapidly addressed.

6.2. Case Study 2: FuelStopY - Challenges Galore

Contrastingly, FuelStopY, situated in a suburban region, faced numerous challenges post their system adoption.

6.2.1. *The Pitfalls*

Despite the advanced system, FuelStopY experienced frequent downtimes attributed to data transmission issues and sensor malfunctions. Moreover, the staff, lacking proper training, often misconfigured the system, leading to operational inefficiencies.

6.2.2. *Lessons Learned*

While the system inherently was not flawed, the lack of infrastructural support, combined with inadequate staff training, highlighted the importance of a holistic approach to IoT adoption. It’s not just about technology, but how it’s integrated into the existing ecosystem.

6.3. Case Study 3: RemoteRefuelZ - Mixed Outcomes

RemoteRefuelZ, a fuel station in a rural locale, presented a mixed bag of results.

6.3.1. *The Achievements*

Being in a remote location, the system’s remote monitoring feature greatly reduced the need for on-site IT staff, leading to significant cost savings. The predictive maintenance alerts ensured that potential issues were addressed proactively.

6.3.2. *The Shortcomings*

However, being in a low-network-coverage area, data transmission was not seamless. Additionally, extreme weather conditions sometimes affected the sensors, leading to temporary system shutdowns.

Table 7: Successful Implementations

Case Study	Success Factors	Key Learnings
Case Study 1	Robust Data Transmission, User Training	Importance of user training for system adoption.
Case Study 2	Redundancy in Hardware, Regular Maintenance	Hardware redundancy enhances system reliability.

Table 8: Challenging Implementations

Case Study	Challenges Faced	Mitigation Strategies
Case Study 1	Data Transmission Delays, User Resistance	Enhanced data transmission infrastructure, Interactive user training sessions
Case Study 2	Sensor Inaccuracies, Software Glitches	Regular sensor maintenance, Continuous software updates

## 7. Recommendations for Future Development

From insights gleaned from performance measurements, real-world challenges, and case studies, it is clear that while IoT-based smart fueling systems offer the potential change, but they require careful planning, adaptation and continuous development. This section provides a series of recommendations to advance technology toward greater efficiency, reliability, and user satisfaction.

Table 9: Recommendations for Future Development

Area	Recommendation
Infrastructure Enhancement	Strengthen data transmission systems to reduce downtimes.
User-Centric Improvements	Implement interactive user tutorials and real-time support channels.
Operational and Maintenance Protocols	Schedule regular system health checks and invest in continuous staff training.
Research and Development	Integrate advanced machine learning models and foster collaborative research initiatives.

### 7.1. Infrastructure Enhancement

#### 7.1.1. Strengthened Data Transmission

Prioritizing investments in robust data transmission infrastructures can mitigate many of the observed system downtimes and lags, especially in rural or remote areas.

#### 7.1.2. Advanced Sensor Protection

The frequent sensor-related issues, exacerbated by external conditions like weather, necessitate the development of more resilient sensor protection mechanisms or the adoption of sensors designed for extreme conditions.

### 7.2. User-Centric Improvements

#### 7.2.1. Interactive User Tutorials

Given the hesitancy of some users in adapting to the new system, interactive tutorials at fueling stations can aid in familiarizing users with the technology, enhancing their confidence and trust.

#### 7.2.2. Real-time Support Channels

Implementing real-time support channels, such as chatbots or helplines, can provide users with instant assistance should they encounter any difficulties or have questions.

### 7.3. Operational and Maintenance Protocols

#### 7.3.1. Regular System Health Checks

Scheduled system health checks, both remotely and on-site, can preemptively identify potential issues, reducing unplanned downtimes.

#### 7.3.2. Continuous Staff Training

Considering the operational errors encountered, a more structured and recurrent staff training program can ensure that the human aspect of operations remains competent and up to date with system evolutions.

### 7.4. Research and Development

#### 7.4.1. Integration of Machine Learning

While the current system utilizes basic algorithms, integrating advanced machine learning models can provide more accurate predictions, optimize fuel dispensing, and enhance user experience.

#### 7.4.2. Collaborative Research Initiatives

Collaborating with academic institutions and tech think-tanks can foster innovative solutions, drawing from a diverse pool of expertise and knowledge.

## 8. Conclusions

The journey into the domain of IoT-based smart fuel filling systems has provided multifaceted insights, reiterating both the transformative potential and challenges of such technological advancements. The intricate interplay of technology, human factors, and environmental conditions shapes the operational landscape of these systems. From the detailed performance metrics, it becomes evident that IoT-based systems, when implemented with precision and maintained rigorously, can lead to unparalleled operational efficiencies, user satisfaction, and economic benefits. System responsive-ness, uptime, and user feedback serves as pivotal indicators of system health and success. However, real-world challenges and case studies emphasize that the theoretical potential of technology doesn't always translate seamlessly into practical applications. Issues related to data transmission, sensor inaccuracies, software glitches, and user reluctance are not just technological hurdles but also underscore the need for continuous user education, staff training, and system upgrades.

For future developments highlight the path forward. It's a roadmap that emphasizes infrastructural enhancements, user-centric improvements, continuous operational protocols, and research collaborations. The integration of advanced machine learning models and especially the enhancement of data streaming infrastructure is the game changers of the future.

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