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Energy conservation in railway tunnel through cloud based automation and geofencing

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Abstract

The Indian railway tunnel lighting systems consume tremendous energy due to all the LEDs inside the tunnel being in the 'ON' state around the clock. In reality, the LEDs should only be in the 'ON' state when the railway passes through the tunnel. According to a survey, the average railway traffic through the tunnel is about 8 hours per day, with the remaining 16 hours being traffic-free. Most of the energy is wasted during this period. The proposed system aims to automate and control tunnel lighting using cloud and geofencing technologies. It can help reduce energy consumption while maintaining safety and lowering LED replacement costs. The system is built on a cloud-based platform and includes various components such as sensors, software, and hardware. These advanced technologies can improve the efficiency of railway infrastructure, reduce energy consumption, and decrease overall costs annually. An analysis of the first 51 tunnels indicated that current energy usage is 76.10 GW, with electricity costs approximately ₹1266.41 million. Implementing an automatic system could reduce energy consumption to 15.86 GW, lowering costs to ₹264.27 million. Energy conservation has a significant societal impact and helps bridge the gap between electricity generation and utilization.

Keywords: Cloud automation, Energy efficiency, Geofencing, IoT, Railway, Tunnel lighting.

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1. Introduction

Railway tunnels require continuous lighting to ensure safety and visibility for trains, passengers, and railway workers. Unlike open railway tracks, where lighting can be adjusted based on operational needs, tunnel lighting is always active, leading to substantial energy consumption and high operational costs. The current lighting systems in tunnels remain switched ON regardless of train movement, resulting in significant energy waste. This inefficiency increases electricity costs and reduces the lifespan of lighting equipment, leading to frequent maintenance and higher operational expenses. As railway networks expand and the global focus shifts toward energy conservation and sustainability, finding an effective, energy-efficient solution for tunnel lighting has become a crucial area of research.

The railway sector is one of the largest electricity consumers, especially in countries with extensive networks such as India, China, and parts of Europe. In India alone, where railways play a vital role in transportation, energy conservation is an urgent concern. This is particularly significant as 62,000 villages in India still lack electricity, making it necessary to use energy efficiently in essential sectors such as railways. Traditional tunnel lighting systems depend on manual switches and timers, which do not account for real-time train movement. Consequently, tunnel lights remain on unnecessarily, leading to wasted electricity, higher costs, and increased maintenance of lighting equipment. Some modern systems utilize motion sensors, but these still do not fully optimize energy consumption, as they react only when motion is detected instead of proactively managing lighting based on train locations and schedules.

To address these challenges, this research explores an automated tunnel lighting system using geofencing technology and cloud-based automation. Geofencing creates virtual boundaries around tunnel entrances, ensuring that lights are activated only when a train is nearby and switched off once it has passed. This method significantly reduces energy waste while ensuring safety is never compromised. Additionally, cloud-based automation allows railway authorities to monitor, control, and adjust lighting remotely in real time. Integrating AI-driven predictive maintenance further enhances system efficiency by detecting and preventing failures before they occur, reducing repair costs and downtime, and improving the lifespan of tunnel lighting infrastructure.

By implementing intelligent lighting control and automated energy management, this research aims to develop a cost-effective, energy-efficient, and technologically advanced solution for tunnel lighting in railways. The proposed system not only minimizes electricity wastage but also supports the broader goal of sustainable energy usage in railway networks. With the help of advanced automation, this approach represents a significant step toward building a smarter, more efficient, and environmentally responsible railway infrastructure.

2. Background and Literature Survey

Indian Railways, established in 1853, has grown into one of the world's largest railway networks, spanning over 68,400 kilometres and connecting 7,349 stations. As the railway network expanded, tunnel construction became essential to navigate India's diverse geographical landscapes, particularly in mountainous regions like the Himalayas and the Western Ghats. Early tunnels were constructed using manual labour and basic tools, often taking years to complete. With technological advancements, longer and more complex tunnels were developed, ensuring uninterrupted railway connectivity. Notable examples include the Karbude Tunnel (6.5 km) and the Rohtang Tunnel (9 km), both of which significantly improved transportation efficiency. However, the continuous need for illumination in these tunnels has resulted in high energy consumption and operational costs, making efficient lighting solutions a crucial area of focus.

Tunnel lighting is a significant contributor to railway energy consumption, as it operates continuously to ensure visibility and safety. Unlike open railway sections that benefit from natural daylight, tunnels lack direct exposure to sunlight and therefore depend entirely on continuous electrical illumination to maintain visibility and safety. Traditional tunnel lighting operates on fixed schedules or manual controls, leading to unnecessary energy usage even when tunnels are unoccupied. Given that Indian Railways is one of the largest electricity consumers in the country, inefficient lighting systems further increase its rising energy demands and financial costs. Additionally, the continuous operation of lighting fixtures reduces their lifespan, increasing maintenance expenses and the frequency of replacements.

Energy consumption in railway systems has been a critical area of research, particularly concerning high-speed trains and urban rail networks. Zhang et al. [1] conducted an in-depth analysis of energy consumption in high-speed trains under real vehicle test conditions, providing insights into power efficiency and operational challenges faced by modern rail systems [1]. Their study highlighted the significant impact of traction power on overall energy consumption and recommended optimizations in train scheduling to enhance efficiency.

Arıkan et al. [2] provided a comprehensive study on energy efficiency in rail systems, emphasizing the importance of infrastructure enhancements and regenerative braking mechanisms to minimize power wastage [2]. Their research examined advanced technological integrations, such as smart grid systems and AI-driven energy management, to optimize power consumption in railway networks.

Nold and Corman [3] explored energy losses in railway vehicles and their impact on energy-efficient train control, emphasizing the role of accurate modeling in mitigating unnecessary power consumption [3]. Their study presented new methodologies for improving train energy efficiency through precise energy loss simulations and predictive control strategies.

Artificial intelligence (AI) has emerged as a transformative technology in railway infrastructure, with Phusakulkajorn et al. [4] reviewing the current research, challenges, and future opportunities in AI-based railway energy management systems [4]. They identified key areas where AI could improve predictive maintenance, optimize train scheduling, and reduce overall energy consumption.

The development of intelligent adaptive tunnel lighting systems has also gained attention in recent years. Musa et al. [5] designed an adaptive tunnel lighting system that adjusts light intensity based on external conditions, leading to significant energy savings [5]. Similarly, Chen et al. [6] Proposed a hybrid lighting system that combines natural light and LED technology to optimize tunnel illumination while reducing electricity consumption [6].

Comparative studies on energy savings in tunnel lighting systems have further reinforced the importance of control strategies. Qin et al. [7] evaluated different energy-saving methods in tunnel lighting and demonstrated how adaptive control mechanisms could lead to significant reductions in energy use [7]. Their research concluded that integrating sensor-based and AI-driven lighting adjustments could improve both energy efficiency and operational safety.

Train running curve optimization has been another area of focus. Deng et al. [8] analyzed the energy consumption of urban rail systems by comparing fast and slow train modes, demonstrating that optimizing train acceleration and deceleration patterns could yield substantial energy savings [8]. Their findings underscored the importance of intelligent scheduling and real-time monitoring in railway energy management.

Recent advancements in rail vehicle energy efficiency were explored by Skobiej [9], who reviewed contemporary technologies aimed at reducing energy consumption in rolling stock [9]. The study emphasized the role of regenerative braking, lightweight materials, and energy storage solutions in enhancing railway sustainability.

Additionally, Kampik et al. [10] examined energy consumption in railway signal boxes, highlighting the potential for optimizing power usage in signalling infrastructure through automation and AI-driven energy management techniques [10]. their study pointed to the necessity of integrating smart control systems to minimize unnecessary energy expenditures in railway operations.

Despite these advancements, existing railway tunnel lighting systems continue to rely on basic automation techniques, such as motion sensors and load cells. While these contribute to energy savings, they lack advanced automation, cloud-based systems, and AI-driven predictive maintenance. A detailed analysis of current tunnel operations indicates that energy consumption for the first 51 tunnels stands at 76.10 GW, resulting in electricity costs of approximately ₹1266.41 million. However, the current focus remains limited to lighting optimization, neglecting broader energy management strategies. By integrating systems, projections suggest that energy consumption could be reduced to 15.86 GW, with costs decreasing to ₹264.27 million. Additionally, existing systems fail to address environmental concerns such as carbon footprint reduction and air quality improvement within tunnels. The absence of integration with smart transportation networks further limits the efficiency of railway infrastructure. Future research should prioritize cloud-based automation and real-time energy monitoring to enhance sustainability and operational effectiveness.

3. Significance

Efficient energy management is crucial in high-energy-consuming sectors such as railways, where unnecessary power consumption in railway tunnels leads to significant energy wastage, increased operational costs, and strain on power resources. A detailed analysis of the first 51 tunnels reveals that the current energy usage stands at 76.10 GW, resulting in electricity costs of approximately ₹1266.41 million. This excessive consumption highlights the pressing need for a more intelligent solution to optimize energy utilization. To address this challenge, this research proposes an automated tunnel lighting system that leverages geofencing and cloud-based control mechanisms, ensuring that tunnel lights are switched on only when necessary. By implementing this system, energy consumption can be significantly reduced from 76.10 GW to 15.86 GW, thereby lowering electricity costs to ₹264.27 million. Beyond economic benefits, this initiative also contributes to environmental sustainability by curbing carbon emissions, reducing the ecological footprint of railway operations, and aligning with India’s clean energy objectives. Excessive electricity consumption not only depletes resources but also exacerbates global warming, making energy efficiency a critical concern. Moreover, railway infrastructure incurs high maintenance costs due to continuous energy consumption and frequent replacement of lighting systems, which this system mitigates through intelligent automation. Additionally, safety and operational efficiency are significantly enhanced through the integration of real-time monitoring and automated emergency response systems. The cloud-based automation aspect of this system allows railway authorities to remotely monitor and control tunnel lighting, ensuring a smart, adaptive, and energy-efficient railway network. The significance of this research extends beyond cost savings, as it directly contributes to national energy conservation efforts, reducing dependency on non-renewable energy sources while improving railway efficiency. By ensuring intelligent power distribution, the saved energy can be redirected to underserved regions, addressing electricity shortages in rural and semi-urban areas. Furthermore, this system enhances operational reliability by reducing unnecessary power loads, preventing network strain, and ultimately fostering a technologically advanced, cost-effective, and sustainable railway infrastructure. The successful implementation of this solution strengthens India’s commitment to smart railway modernization while promoting a more energy-efficient, environmentally friendly, and resource-optimized transportation framework for the future.

4. Proposed Methodology

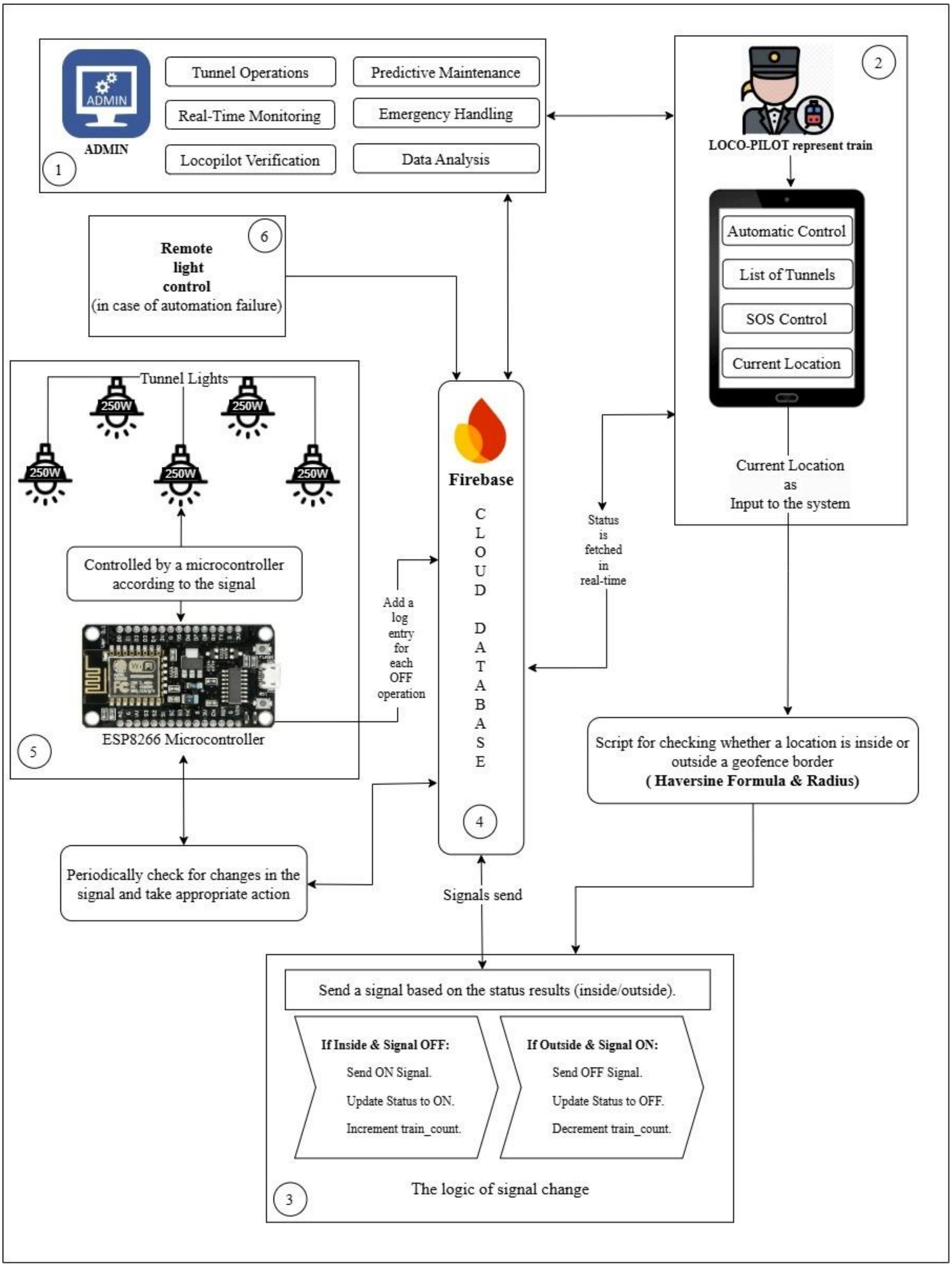

Figure 1.
Block Schematic Showing Integration of Cloud and Automation.

The above architecture presents an automated tunnel lighting regulation solution using real-time train location data. It comprises six core components: The Admin Panel, which provides centralized control for tunnel operations, monitoring, and emergency handling; The Loco-Pilot Device (LPD), which represents the train and sends current GPS location data to the system while offering features like automatic control and SOS management; The Signal Logic Handler, which processes location data using geofencing (Haversine formula) to determine whether the train is inside or outside the tunnel and sends ON/OFF signals accordingly; The Firebase Cloud Database, which acts as the communication bridge for storing and updating real-time light status and logs; The ESP8266 Microcontroller, which receives signals from Firebase to control the tunnel lights and periodically checks for updates; and The Remote Light Control, which enables manual override by the admin in case of automation failure. This integrated system ensures energy efficiency, safety, and intelligent management of tunnel lighting in railway operations.

4.1. System Architecture

The system's architecture centers on the real-time monitoring of trains and their distance from tunnels, facilitating the autonomous regulation of tunnel lighting. The primary elements consist of the Loco Pilot Device (LPD), which directly connects with the train operator, and the cloud-based database that oversees the state of tunnel lights. The ESP8266 microcontroller at each tunnel regulates the lighting apparatus according to real-time data. An Admin Panel functions as the control and monitoring center for supervising the whole system operation, facilitating efficient administration and predictive maintenance.

The system functions in real-time, delivering automatic lighting management by utilizing geolocation data sent by the LPD. The cloud database synchronizes information and processes data to ascertain the status of the tunnel lights, thereby reducing energy consumption while ensuring safety for passengers and operators.

4.2. Locomotive Pilot Device (LPD) with Geofencing

The Loco Pilot Device is a portable, intuitive interface that provides real-time operational information to the train operator. It continuously tracks the train's location using geolocation methods. The device employs geofencing to accurately monitor the train's proximity to tunnels, facilitating location-based lighting management.

The train's position is ascertained using the Haversine formula, which computes the great-circle distance between two locations on the Earth's surface. The technology employs a radius-based methodology to delineate a geofenced zone surrounding each tunnel. Upon the train's entry into this geofenced zone, the LPD transmits a signal to the cloud, activating the tunnel lights. Correspondingly, upon the train's departure from the vicinity, the system disables the lights. This method identifies whether the train is inside or outside the geofence. The geofence is circular in shape.

4.2.1. The Haversine Equation is Utilized to Calculate the Distance between the User's Current Location and the Geofences Surrounding the Tunnel

$$a = \sin^2\left(\frac{\Delta\varphi}{2}\right) + \cos(\varphi_1)\cdot\cos(\varphi_2)\cdot\sin^2\left(\frac{\Delta\lambda}{2}\right)$$

$$c = 2\cdot \operatorname{atan2}\left(\sqrt{a}, \sqrt{1-a}\right) \quad (1)$$

$$d = R\cdot c$$

where:

- d: The distance between the two points.
- R: The radius of the sphere (for Earth, approximately 6371 km or 3958.8 miles).
- $\phi 1,\phi 2$: Latitudes at point1& point 2 respectively (in radians).
- $\lambda 1,\lambda 2$: Longitudes at point 1 & point 2 (in radians).
- $\Delta\phi=\phi 2-\phi 1$: latitude difference.
- $\Delta\lambda=\lambda 2-\lambda 1$: longitude difference.

A tan2(y,x): A function used to calculate the angle between the positive x-axis and the point (x, y), ensuring proper quadrant determination

This geofencing technique guarantees that tunnel illumination is triggered solely when required, thereby improving energy efficiency by reducing electricity consumption. The LPD incorporates an SOS (Distress Signal) button and hands-free voice operation, allowing the train operator to execute emergency procedures swiftly during normal circumstances.

4.2.2. Mathematical Model for Estimating Train Arrival Time at a Tunnel

The estimated arrival time (ETA) at the tunnel is determined using the basic motion equation:

$$T = \frac{S}{D} \quad (2)$$

where:

- T = Time required to reach the tunnel (hours)
- D = Distance to the tunnel (km)
- S = Current speed of the train (km/hr)

Since train speed varies due to signals, curves, or station halts, we introduce the last known speed ($\boldsymbol{S_L}$)

$$S = \max(S, S_L) \quad (3)$$

To get the estimated arrival time, we add the computed travel time to the current time

$$ETA = t_0 + T \quad (4)$$

4.2.3. Example Calculation

Consider a train that is 10 km away from a tunnel and moving at 40 km/hr, with the current time being 14:00 (2:00 PM):

T = 40/10 = 0.25 hours = 15 minutes

ETA = 14: 00 + 15 minutes = 14: 15 (2: 15 PM)

The ETA remains valid if the train stops and resumes at its last known speed of 40 km/hr.

4.3. Administrative Interface and Operational Oversight

The Admin Panel offers a comprehensive interface for system management, facilitating real-time monitoring, data analysis, predictive maintenance, and manual control functionalities. It enables system administrators to supervise the status of tunnel lights, track train locations, and evaluate operational data for optimization prospects. The Admin Panel oversees loco pilot verification and emergency management, providing centralized control under atypical circumstances or breakdowns. The automatic light control system can be manually overridden if necessary, guaranteeing the operational safety of the entire tunnel network under all conditions. The Admin Panel is essential for predictive maintenance, employing data analytics to detect possible issues and proactively mitigate system failures before they arise.

4.3.1. Mathematical Model for Energy Savings After Optimization

Let:
P = Power consumption per light in watts (W)
N_{lights} = Total number of lights in the tunnel (1000 lights)
H_{before} = Hours the lights were ON before optimization (24 hours)
H_{after} = Hours the lights are ON after optimization (5 hours)
E_{before} = Energy utilization before optimization (in kWh)
E_{after} = Energy utilization after optimization (in kWh)
S = Energy saved (in kWh) S = Percentage energy saved

4.3.2. Energy Consumption Before Optimization

Before optimization, lights were ON 24/7, so the total energy usage was:

$$E\text{before} = P \times N\text{lights} \times H\text{before} \quad (5)$$

where:

- P = Power consumed by each light (in watts)
- Nlights = Number of lights
- Hbefore = Number of hours lights are ON before the innovation

Example Calculation (for Karbude Tunnel)
$P = 250W$
$N_{\text{lights}} = 1000$
H_{before} = 24 hours

$$E_{\text{before}} = 250 \times 1000 \times 24 = 6000 \text{ kWh}$$

4.3.3. Energy Consumption After Optimization

After implementing the system, the lights are ON for 5 hours instead of 24 hours.

$$E_{\text{after}} = P \times N_{\text{lights}} \times H_{\text{after}} \quad (6)$$

where:

- P = Power consumed by each light (in watts)
- Nlights = Number of lights
- H_{after} = Number of hours lights are ON after the innovation

Example Calculation
$E_{\text{after}} = 250 \times 1000 \times 5 = 1250$ kWh

4.3.4. Energy Saved

The energy saved is given by:

$$S = E_{\text{before}} - E_{\text{after}} \quad (7)$$

Example Calculation
$S = 6000 - 1250 = 4750$ kWh

4.3.5. Percentage Energy Saved

$$S = \left(\frac{S}{E_{\text{before}}}\right) \times 100 \quad (8)$$

Example Calculation

$$S = \left(\frac{4750}{6000}\right) \times 100 = 79.17\%$$

Table 1.
Energy Consumption Overview: Pre-Innovation Analysis.

Tunnel Name	No. of Bulbs used	Energy Consumption Units/Year
Tike (T-39)	676	1480440
Patalpani Rail Tunnel	680	1489200
Nathuwadi (T-6)	718	1572420
Maliguda Tunnel	723	1583370
Karbude (T-35)	1000	2190000
Malekhara	1000	2190000
Rapuru (P-4)	1019	2231610
Thane Creek Tunnel	1067	2336730
Sangaldan tunnel	1080	2365200
Trivandrum Port Tunnel	1336	2925840
Teestabazar (T-16)	1336	2925840
Keylong Tunnel	1336	2925840
Pir Panjal railway tunnel	1628	3565320
Kalijhora Tunnel (T-13)	1628	3565320
Saheilbung tunnel (T -12)	1674	3666060
Tunnel T50	1836	4020840
Devprayag Rail Tunnel	2147	4701930

Table 1 presents data on the annual energy consumption of various railway tunnels based on the number of bulbs used. Each entry lists the tunnel name, the total number of bulbs installed, and the corresponding yearly energy consumption in units. This information provides insight into the scale of energy usage across different tunnels, reflecting how longer tunnels or those with more extensive lighting infrastructure tend to consume more energy annually. The data serves as a reference point for assessing potential energy-saving opportunities through improved lighting technologies or automation.

4.4. Quick Comparison between Tunnels

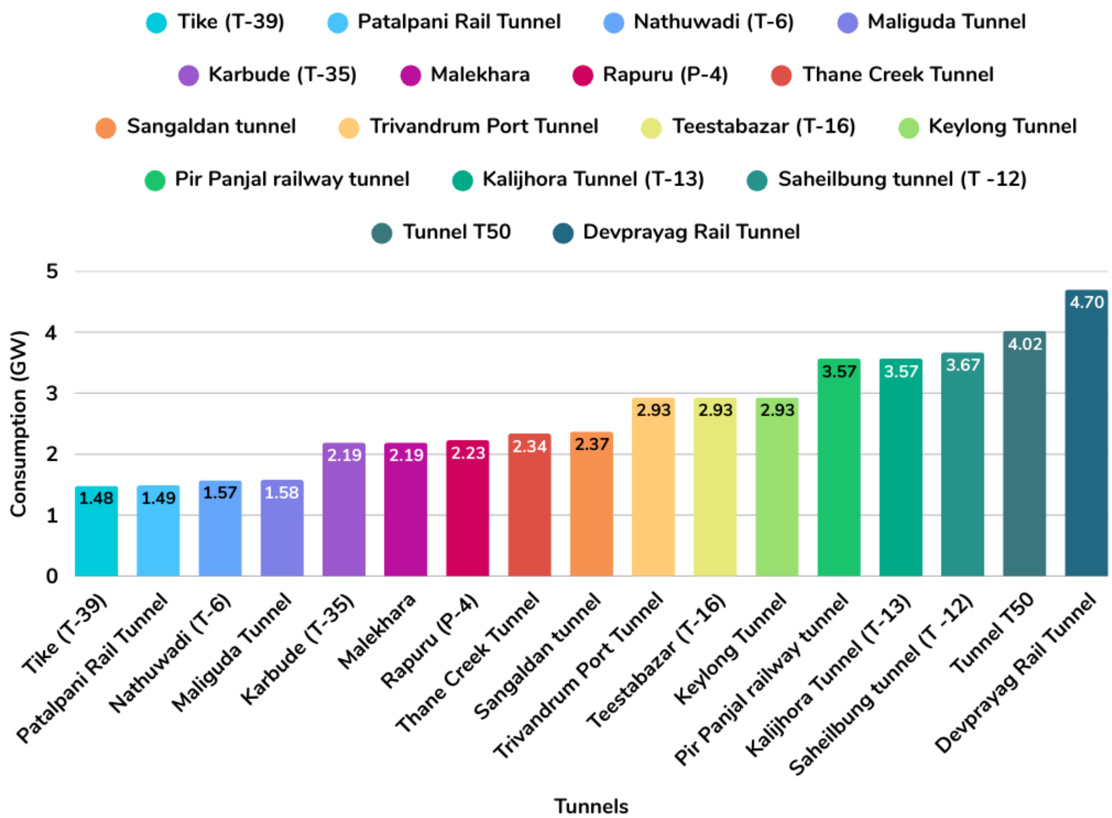

Figure 2.
Energy Consumption Visualization: Pre-Innovation Analysis.

Figure 2 illustrates the pre-innovation annual energy consumption of various railway tunnels in GW. It provides a clear comparison of energy usage before any energy-efficient technologies were introduced. Among the tunnels, Tike (T-39) had the lowest consumption, whereas the Devprayag Rail Tunnel exhibited the highest. This visual representation establishes a baseline for evaluating the impact of subsequent innovations in energy efficiency.

4.5. Mathematical Model for Bulb Counting Data

- Length of Karbude (T-35) Tunnel: 6.5 km
- Length of Train: 1 km
- Total Distance to Cross the Tunnel: 6.5 km + 1 km 7.5 km
- Speed of Train: 50 km/hr
- Time to Cross Tunnel:

Time= (7.5 km / 50 km/hr) × 60 minutes = 9 minutes

Number of Bulbs and Power Consumption

- Power Consumption of Each Bulb: 250W
- Distance Between Bulbs: 15 meters

To calculate the total number of bulbs required for both sides of the tunnel, it is necessary to consider that the bulbs are placed 15 meters apart on each side of the tunnel.

Length of Karbude (T-35) Tunnel: 7.5 km, so the total length of the tunnel for both sides (for bulb placement) is:

Total Length = 7.5 km×2=15 km= 15,000 meters

Total Number of Bulbs = 15,000 meters/15 meters = 1000 bulbs

4.6. Mathematical Model for Predicting Maintenance & Replacement Dates of Tunnel Lights

4.6.1. Definition of Variables

Let:

$$U_{\text{Karbude}} = \sum_{j=1}^{n} W_j \quad (9)$$

(Total usage hours per month, sum of individual working hours per day for tunnel lights)

Where*:*

- Wj: Working hours of tunnel lights on day j.
- j: Daily index ranging from 1 to n.
- n: Total number of days in the observation period (typically one month).

L_{lifespan} = 10,000 hours (Lifespan of each tunnel light)

M_{interval} = 6 months (Maintenance interval for tunnel lights)

D_{install} = Installation date of tunnel lights

Dnext_maintenance = Next maintenance date

$D_{\text{replacement}}$ = Predicted replacement date

4.6.2. Calculation of Next Maintenance Date for Tunnel Lights

Tunnel lights require maintenance every 6 months from the installation date: Dnext_maintenance = Dinstall + Minterval (10) Example Calculation

If the installation date is January 1, 2024:

$D_{\text{next\_maintenance}}$ = January 1, 2024 + 6 months = July 1, 2024

4.6.3. Calculation of Replacement Date for Tunnel Lights

The replacement date is determined by the total usage hours reaching the lifespan limit. The total usage per month is given by:

$$U_{\text{Karbude}} = \sum_{j=1}^{n} W_j \quad (11)$$

Thus, the replacement date is:

$$D_{\text{replacement}} = D_{\text{install}} + \frac{U_{\text{Karbude}}}{L_{\text{lifespan}}} \quad (12)$$

Example Calculation

Assuming each tunnel light operates for 5 hours per day for 30 days in a month:

$U_{\text{Karbude}} = 5 + 5 + 5 + \cdots + 5 = 150$ hours per month

$$D_{\text{replacement}} = D_{\text{install}} + \frac{10{,}000}{150}$$

Dreplacement = Dinstall + 66.67 months ≈ 5.56years

Example Output

If installation date = January 1, 2024:

- Next Tunnel Light Maintenance Date → July 1, 2024

- Tunnel Light Replacement Date → Around July 2029

4.6.4. Geofence Radius Selection for Tunnel

To ensure that the geofence covers the entire tunnel and allows early train detection, we calculate the radius as:

$$R = \frac{2}{L} + d + M \tag{13}$$

where:

- L = Tunnel length
- d= Early detection distance before tunnel entry
- M= Safety margin

Example: Karbude Tunnel

- Tunnel Length: L=6.5 km
- Early Identification Distance: d=2.5 km
- Buffer Margin: M=0.5 km

$$\boldsymbol{R = \frac{2}{6.5} + 2.5 + 0.5 = 0.3077 + 2.5 + 0.5 = 3.25 + 2.5 + 0.5 = 6.25} \text{ km}$$

4.6.5. Final Geofence Radius: 6.25 km

This ensures full tunnel coverage while allowing the train to be detected 2.5 km before entering the tunnel, optimizing response time without excessive geofencing.

4.7. Cloud Integration and Microcontroller Management

The cloud database is the core of the system, functioning as the primary repository for all operational data, such as the train's location, tunnel light status, and overall system performance. The cloud continuously receives information from the LPD concerning the train's real-time location and then adjusts the status of the tunnel lights (ON/OFF) based on the train's presence within the geofenced area. The ESP8266 microcontroller is essential for managing the tunnel lights. This microcontroller persistently interrogates the cloud database to obtain the current state of the lights. Upon a train's entry into the tunnel's geofenced zone, the cloud directs the ESP8266 to activate the lights; conversely, upon the train's departure, the ESP8266 receives an order to deactivate the lights. A fail-safe mechanism is incorporated into the ESP8266 to ensure system reliability. In the event of a communication failure with the cloud database, the system immediately activates the lights to maintain illumination in the tunnel for safety, thereby averting potential mishaps.

4.8. Energy Efficiency and Safety

The principal objective of this methodology is to enhance energy efficiency while upholding safety criteria. The system conserves electricity by activating the lights solely when the train is in the tunnel and deactivating them upon exit. Tunnel lights are activated in real-time according to the train's position, ensuring compliance with lighting regulations while minimizing energy use. The system's failsafe function guarantees uninterrupted illumination during communication failures, thereby averting dark areas in the tunnel that may present safety hazards. The incorporation of predictive maintenance significantly improves the safety and reliability of the system by diminishing the probability of equipment failure and prolonging the lifespan of the lighting system.

4.9. System Workflow

The system's operational flow comprises several essential steps:

Position Detection: The LPD employs geolocation methods to determine the train's position and updates the cloud with the train's real-time location.

Geofencing: The technology uses the Haversine formula to determine the train's distance from the tunnel and contrasts it with established geofenced zones.

Light regulation: Utilizing positional data, the cloud modifies the tunnel light state (ON/OFF), which is subsequently accessed by the ESP8266 microcontroller to regulate the lighting system.

Admin Monitoring: The Admin Panel facilitates real-time oversight of system performance, manual intervention, and anticipatory maintenance for enhanced efficiency. This method combines real-time geolocation, cloud synchronization, and microcontroller-based management to create an efficient and dependable system for managing tunnel illumination in railway networks.

5. Results and Discussion

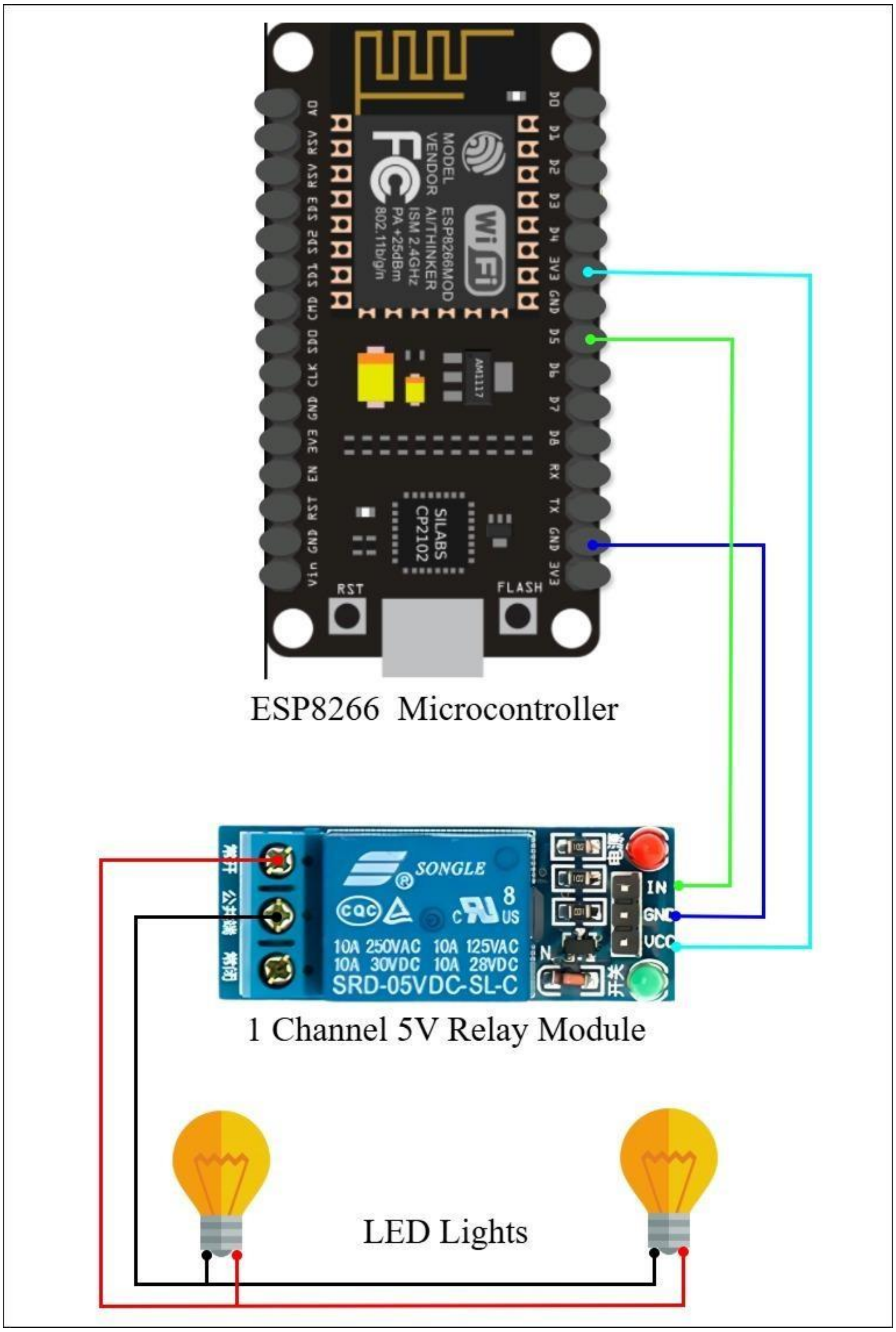

Figure 3.
Circuit Diagram for Automated Tunnel Lighting Control.

Figure 3 illustrates the circuit diagram of a tunnel lighting control system utilizing an ESP8266 microcontroller, a 1-channel 5V relay module, and LED lights wired in series. The ESP8266 microcontroller serves as the central control unit, managing the relay module through its GPIO pins. The relay module acts as an electronic switch, controlling the power supply to the LED lights based on programmed instructions. The LED lights are connected in series, sharing the same current flow to ensure synchronized operation. This setup enables efficient and automated lighting control, optimizing energy usage in tunnel environments.

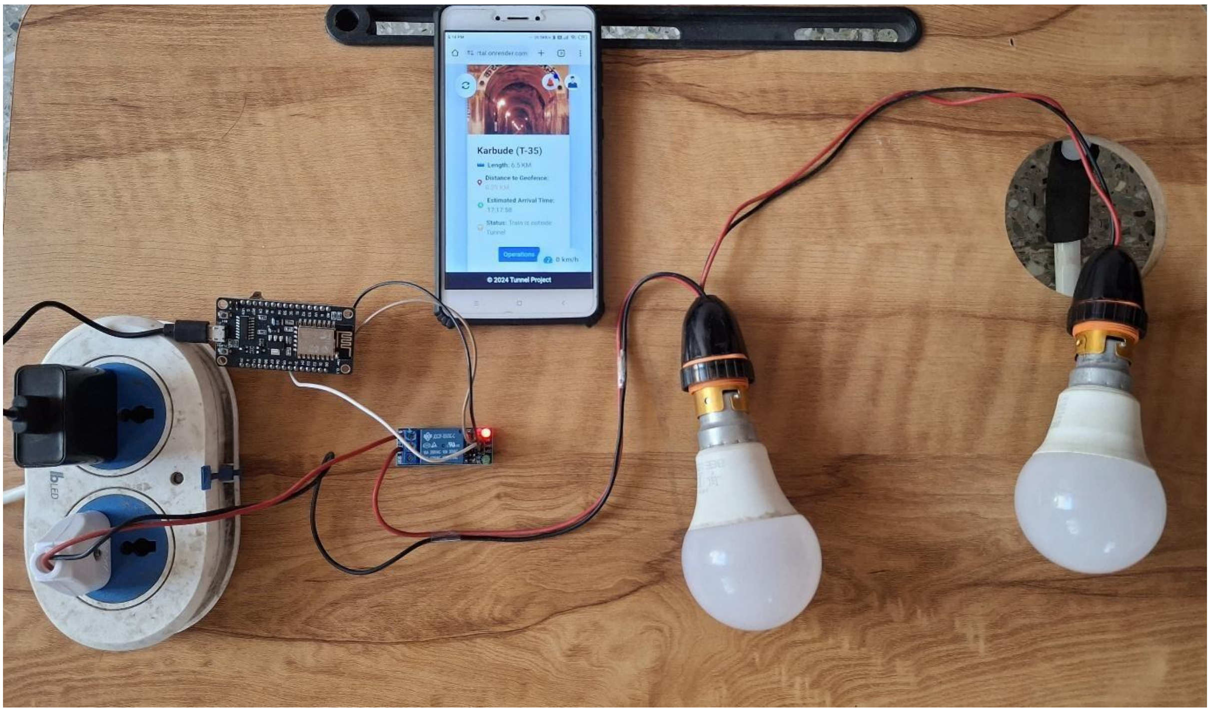

Figure 4.
Implementation and Demonstration of IoT-Enabled Smart Tunnel Lighting System.

Figure 4 demonstrate setup showcases the IoT-enabled smart tunnel lighting system, incorporating an ESP8266 microcontroller as the central processing unit for real-time control and automation. A 5V single-channel relay module is integrated to regulate the power supply to the tunnel lights, ensuring efficient switching mechanisms based on geofencing triggers. The lighting system is designed with series wiring, where multiple lights share the same current flow, optimizing electrical connectivity and minimizing power losses. This configuration enables synchronized illumination control, ensuring that energy is utilized effectively while maintaining operational stability. The deployment of these IoT components demonstrates the feasibility of implementing intelligent tunnel lighting automation, reducing unnecessary power consumption and improving railway infrastructure efficiency.

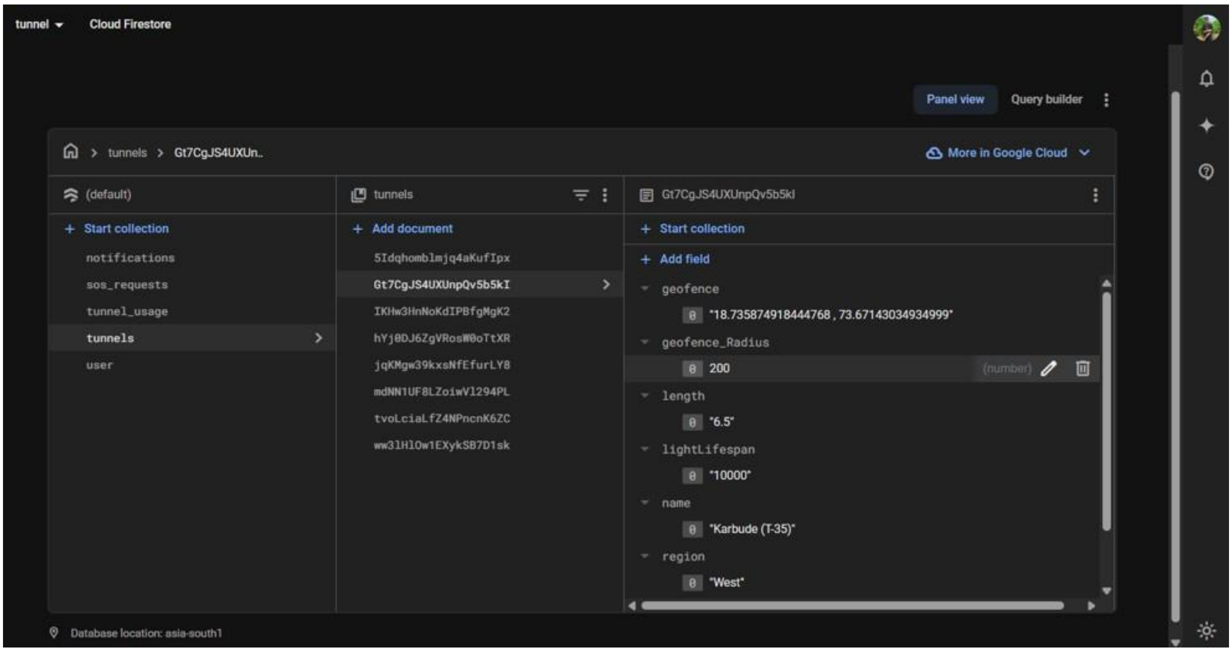

Figure 5.
Cloud Console-Integrated Real-Time Database Architecture for Tunnel Monitoring and Energy Management.

Figure 5 represents the real-time database framework that stores comprehensive details of each tunnel, including real-time parameters such as tunnel length, geofence coordinates, lighting lifespan, and other critical operational data. It enables efficient monitoring and management, ensuring optimized energy usage and predictive maintenance.

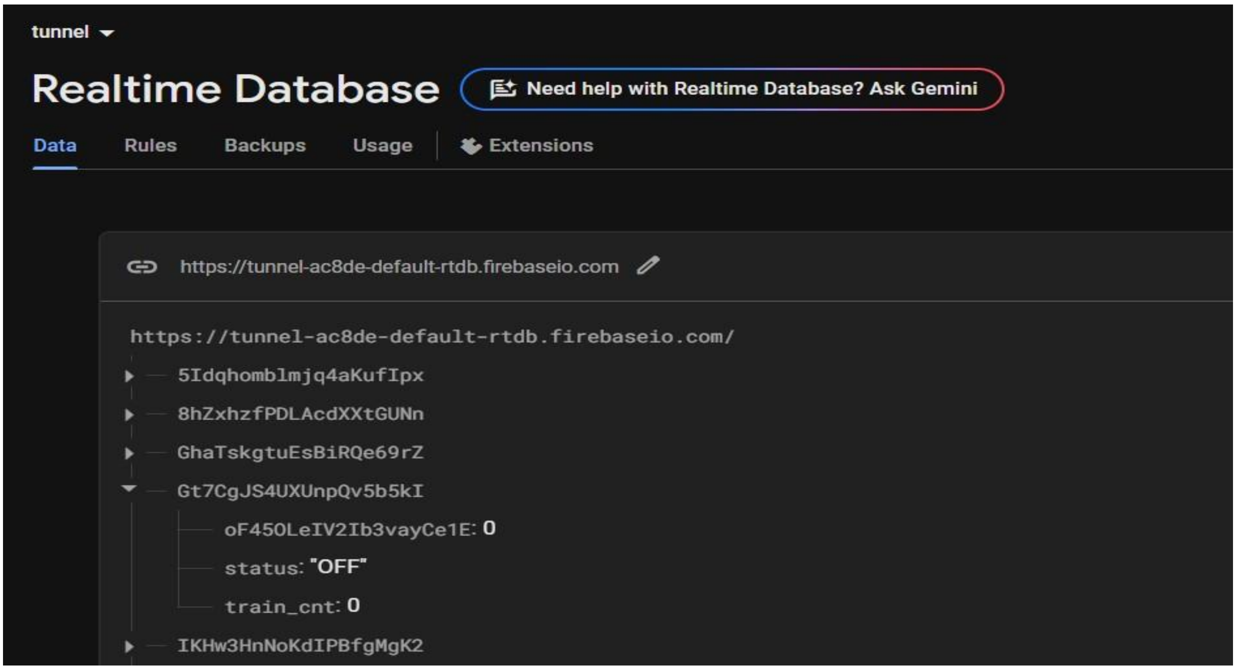

Figure 6.
Real-Time Status of Tunnel Lights Being Turned Off.

Figure 6 represents the real-time status of tunnel lights being turned off, demonstrating the energy-saving mechanism implemented in the system. This status aligns with the automated control logic. shown in Figure 2, where lights are managed based on train movement and geofencing parameters to optimize energy usage efficiently.

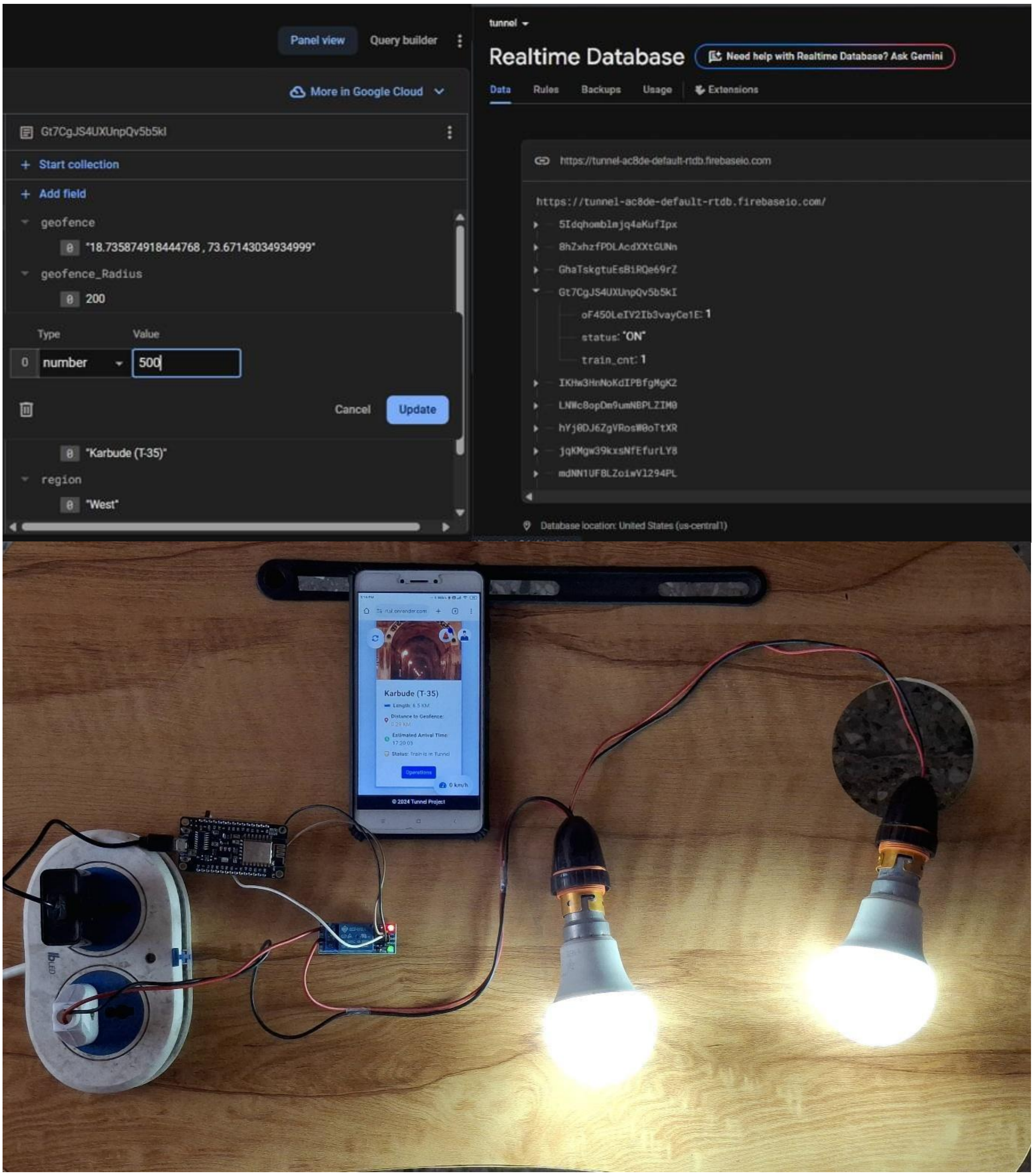

Figure 7.
Dynamic Tunnel Light Activation Based on Geofence Radius Detection.

The Figure 7 demonstrates the prototype implementation of an automated tunnel lighting system designed to operate dynamically based on a train's proximity, determined via geofencing logic. The setup includes two LED bulbs, a relay module, a microcontroller (such as ESP8266), and a power source. The microcontroller is programmed to interface with real-time location data, received wirelessly, to control the activation of the tunnel lights.

As the train approaches the tunnel and enters a predefined geofence radius, the system instantly detects this positional change. Upon crossing the geofence boundary, the microcontroller triggers the relay module to switch the bulbs to an ‘ON’ state. This activation ensures that illumination is provided precisely when and where it is needed, reducing unnecessary energy consumption.

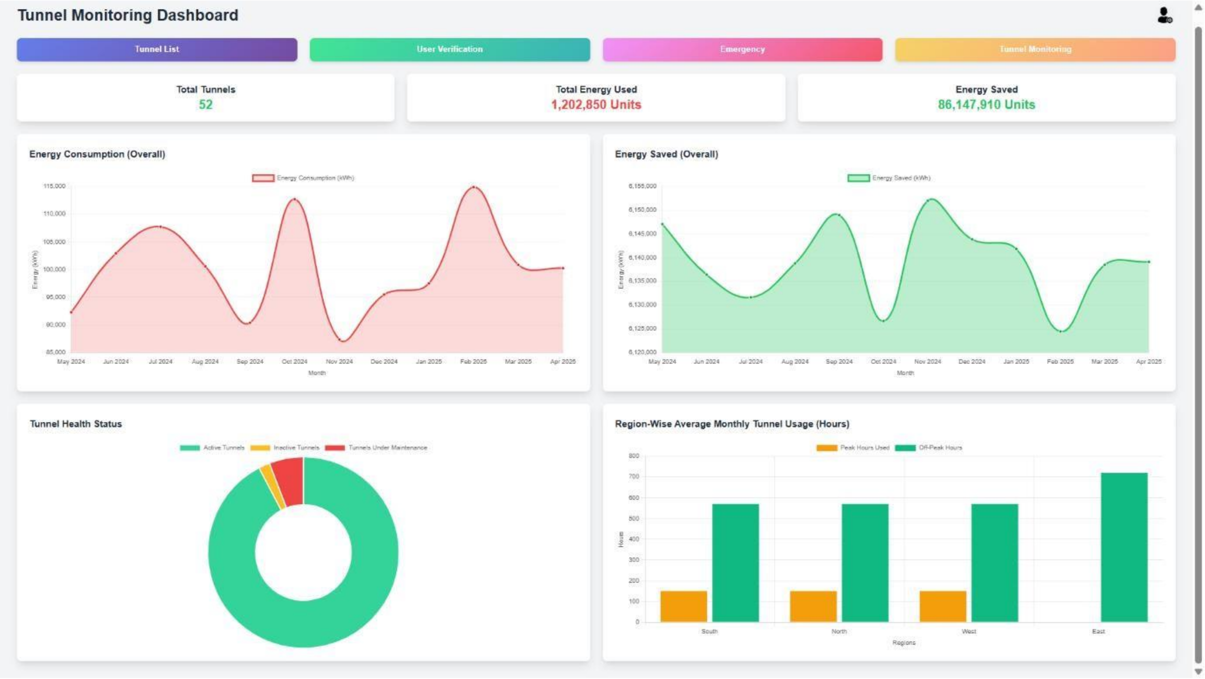

Figure 8.
Real-Time Administrative Dashboard for Tunnel Energy Management.

Figure 8 demonstrates a dashboard prototype that provides a comprehensive overview of tunnel infrastructure, enabling real-time monitoring of total energy consumption, energy savings, and tunnel health status. It also visualizes region-wise average monthly tunnel usage, supporting data-driven decision-making for sustainable and efficient tunnel lighting systems.

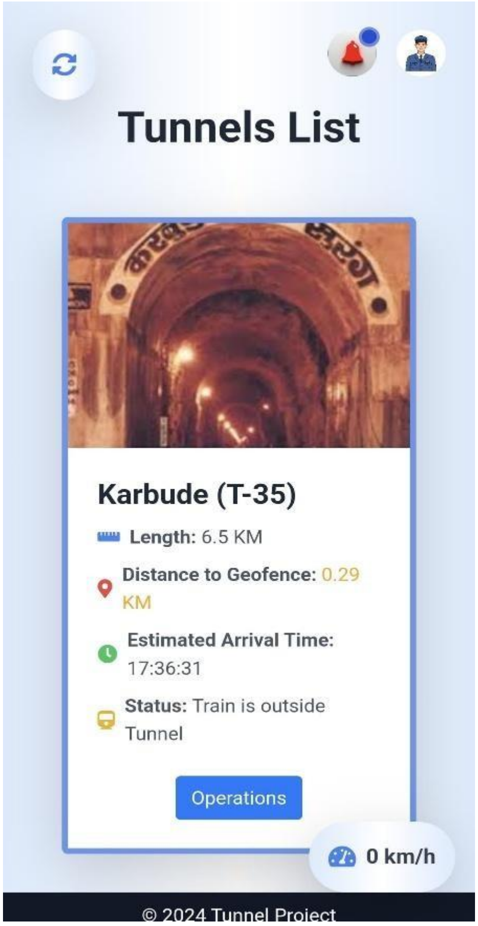

Figure 9.
Loco-Pilot Tunnel Interaction Interface.

Figure 9 shows an interface that enables the loco-pilot to access real-time information about nearby tunnels, including tunnel ID, geofence proximity, estimated arrival time, and current train status. The interface also supports emergency (SOS) alerts and allows remote operations for tunnel-specific control, ensuring safety and operational efficiency.

Table 2.
Energy Consumption Overview: Pre and Post-Innovation Analysis.

Tunnel Name	No. of Bulbs used	Pre-Innovation Energy Consumption Units/Year	Post-Innovation Energy Consumption Units/Year
Tike (T-39)	676	1480440	308425
Patalpani Rail Tunnel	680	1489200	310250
Nathuwadi (T-6)	718	1572420	327587.5
Maliguda Tunnel	723	1583370	329868.75
Karbude (T-35)	1000	2190000	456250
Malekhara	1000	2190000	456250
Rapuru (P-4)	1019	2231610	464918.75
Thane Creek Tunnel	1067	2336730	486818.75
Sangaldan tunnel	1080	2365200	492750
Trivandrum Port Tunnel	1336	2925840	609550
Teestabazar (T-16)	1336	2925840	609550
Keylong Tunnel	1336	2925840	609550
Pir Panjal railway tunnel	1628	3565320	742775
Kalijhora Tunnel (T-13)	1628	3565320	742775
Saheilbung tunnel (T 12)	1674	3666060	763762.5
Tunnel T50	1836	4020840	837675
Devprayag Rail Tunnel	2147	4701930	979568.75

Table 2 provides a comparative overview of energy consumption before and after the implementation of an innovative tunnel lighting control system across various railway tunnels. It includes the name of each tunnel, the number of bulbs used, and the annual energy consumption (in units) before and after the innovation. The data clearly shows a significant reduction in energy consumption post-implementation, highlighting the effectiveness of the automated lighting system in improving energy efficiency across different tunnel lengths and infrastructure setups.

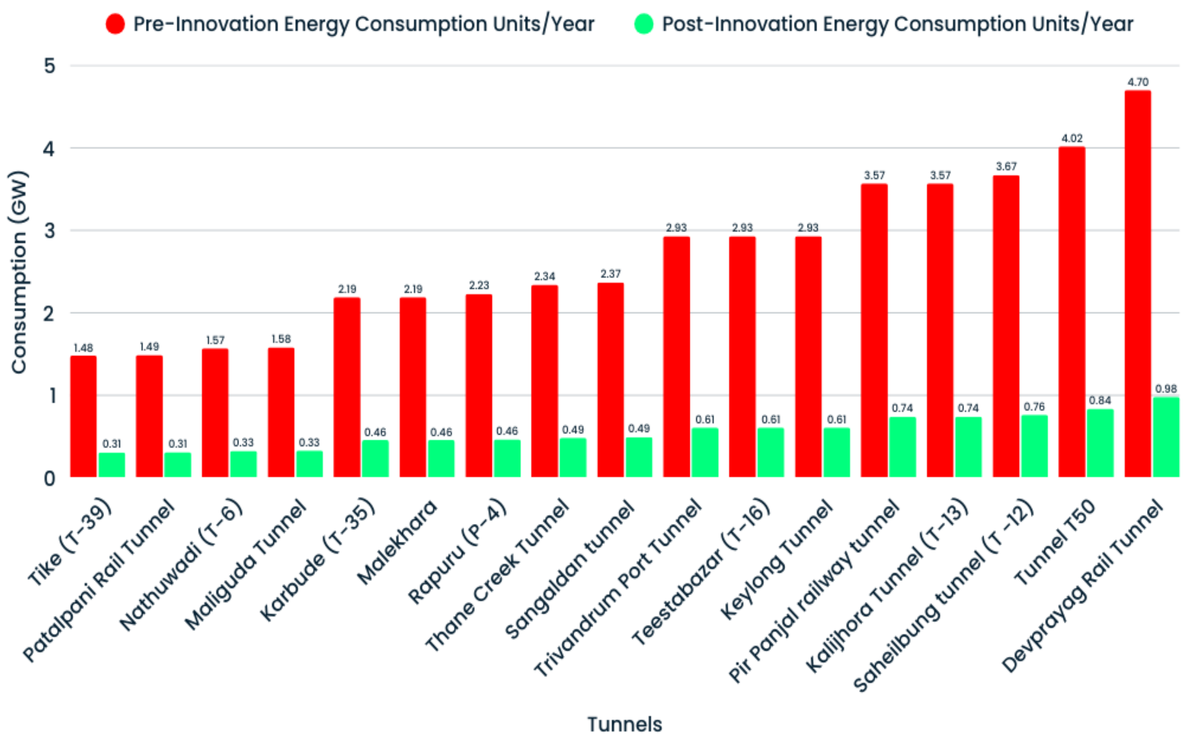

Figure 10.
Energy Consumption Visualization: Pre and Post-Innovation Impact.

Figure 10 illustrates a comparative analysis of energy consumption in GW per year across 17 major tunnels, showcasing values before and after the implementation of innovation. The red bars indicate pre-innovation consumption, while the green bars highlight the significantly reduced energy usage post-innovation. Every tunnel demonstrates a notable decrease in energy consumption, emphasizing the success of the innovative measures adopted. The Devprayag Rail Tunnel shows the most significant drop, from 4.70 GW to 0.98 GW, followed by Tunnel T50 and the Saheilbung Tunnel. Even tunnels with relatively lower initial consumption, such as Tike (T-39) and Patalpani Rail Tunnel, experienced substantial efficiency gains. Overall, Figure 8 reflects the impactful role of innovation in enhancing energy efficiency across tunnel infrastructure.

6. Conclusions

The proposed system presents an effective approach to improving energy efficiency and sustainability in railway tunnel operations. By utilizing smart technology to regulate lighting based on train proximity and incorporating AI-driven predictive maintenance, the system significantly reduces energy consumption, operational costs, and maintenance expenses. An analysis of the first 51 tunnels indicates that the current energy usage is 76.10 GW, with electricity costs amounting to approximately ₹1266.41 million. With the implementation of the proposed solution, energy consumption can be reduced to 15.86 GW, lowering costs to ₹264.27 million. This considerable reduction not only enhances cost-effectiveness but also minimizes environmental impact. Adopting these advanced technologies enhances railway operations and supports the worldwide transition to sustainable transportation. Successfully adopting this system in railway tunnels will result in a more efficient, eco-friendly, and economical railway infrastructure, benefiting both the industry and society.

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