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Enhancing sustainability and energy conservation in Indian railway tunnels through innovative lighting control and predictive maintenance

Mukil Alagirisamy[1], Sagar Shinde[2*], Pranav Nikumbh[3], Karan Jadhav[4], Nikita Jadhav[5]

[1,2]*Asia Pacific University of Technology and Innovation. Malaysia.*
[3,4,5]*PCETS – NMVPMs Nutan Maharashtra Institute of Engineering and Technology, Pune, India.*

Corresponding author: Sagar Shinde (*Email: sagar.shinde5736@gmail.com*)

Abstract

The proposed innovation presents an innovative method for optimizing energy consumption and maintenance in railway tunnel operations, responding to the urgent need for sustainable and cost-effective infrastructure. This solution utilizes advanced geofencing technology integrated with a powerful cloud-based automation platform to guarantee accurate control of tunnel illumination and infrastructure management. The technology optimizes illumination levels in real-time according to train location, speed, and movement patterns, thereby minimizing energy waste, substantially lowering operational costs, and improving safety standards. The cloud platform functions as a single hub for overseeing and administering the tunnel's essential infrastructure, facilitating the seamless integration of real-time diagnostics, predictive maintenance algorithms, and automatic anomaly detection. In cases of system abnormalities, the platform enables swift remote intervention, hence ensuring system dependability and reducing downtime. This holistic strategy not only tackles the urgent operating issues of railway systems but also aligns with long-term sustainability objectives by fostering energy conservation and minimizing environmental impact. This breakthrough enhances operational efficiency and dependability, providing a transformative solution for contemporary railway networks and facilitating the development of greener, more intelligent transportation systems.

Keywords: Cloud-based automation, Energy conservation, Energy optimization, Railway tunnels, Geofencing, Maintenance savings, Real-time diagnostics, Tunnel lighting efficiency.

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1. Introduction

The railway industry functions as a fundamental component of global transportation, facilitating the efficient transit of passengers and cargo while promoting economic development and connection. In nations with significant railway systems, such as India, China, and certain regions of Europe, railways are crucial for national transportation and commerce. India, with one of the largest railway systems globally, illustrates the sector's vital significance. Nonetheless, the magnitude of processes results in significant energy consumption, exerting considerable strain on energy supplies. The difficulty is intensified by the nation's energy access inequality, as more than 62,000 villages remain without electricity, underscoring the critical necessity for energy conservation and effective resource management in essential infrastructure sectors like railways.

Tunnel illumination is a major factor contributing to energy inefficiency in the railway sector. Tunnels are vital elements of railway systems, facilitating secure and uninterrupted operations over various landscapes. Nonetheless, tunnel lighting systems, engineered for continuous operation for safety purposes, incur substantial electrical expenses and demonstrate inefficient resource utilization. Current solutions, including manually operated systems and timer-based controls, do not consider real-time train movement, resulting in lights remaining illuminated despite the lack of train action. This problem is most evident in tunnels longer than 1 kilometer, where energy loss is significant and operational expenses are excessively elevated.

The inefficiencies of existing systems surpass mere energy usage. The uninterrupted running of lighting systems diminishes equipment longevity, resulting in frequent maintenance needs and elevated expenses. Emerging technologies, such as motion sensors, provide limited solutions by activating lights in response to observed movement; however, these systems do not possess the sophistication required to thoroughly optimize energy usage or adapt to the evolving demands of contemporary railway networks.

As worldwide focus transitions to sustainability and energy efficiency, the railway sector must use more intelligent and innovative energy management systems to address these concerns. The suggested system presents an innovative approach that combines geofencing technology with a cloud-based automation platform to address this demand. Geofencing establishes virtual perimeters within tunnel systems, facilitating the accurate activation of lights according to real-time train location, velocity, and movement patterns. This guarantees that tunnel lights are activated solely when and where required, considerably decreasing energy usage.

In addition to geofencing, the system utilizes a cloud-based platform for centralized monitoring and control of tunnel infrastructure. The gathering and analysis of real-time data facilitate effective decision-making, while AI-driven predictive maintenance algorithms guarantee prompt interventions to avert system failures. By detecting maintenance requirements prior to their escalation, the system mitigates downtime, prolongs the longevity of infrastructure, and diminishes operating interruptions. These attributes collectively improve the efficiency, dependability, and sustainability of railway operations.

The execution of this integrated system not only rectifies energy inefficiencies but also conforms to wider environmental and economic goals. The technology enhances a greener and more sustainable transportation ecosystem by diminishing electricity usage, operational expenses, and carbon emissions. Moreover, the implementation of modern technologies such as geofencing, cloud automation, and AI-driven analytics establishes the railway sector as a frontrunner in the shift towards intelligent and sustainable infrastructure.

This article provides a comprehensive examination of the proposed system, emphasizing its technological capabilities, operational benefits, and possible influence on the railway sector. This idea seeks to transform tunnel lighting management by utilizing cutting-edge technologies, setting a new standard for energy efficiency and sustainability in railway infrastructure.

2. Literature Survey

Established in 1853, Indian Railways has evolved into one of the greatest railway networks worldwide, extending over 68,400 kilometers and linking 7,349 stations. The extension of this extensive network has encountered obstacles due to India's varied physical landscapes, necessitating the construction of tunnels, particularly through mountain ranges such as the Himalayas and Western Ghats. The initial tunnels were constructed with manual labor and rudimentary tools, frequently requiring years for completion. With the expansion of the network, the necessity for larger tunnels emerged, exemplified by the Karbude Tunnel (6.5 km) and the Rohtang Tunnel (9 km), highlighting the critical role of tunnels in sustaining connectivity. Nonetheless, these tunnels necessitated continuous illumination and ventilation to maintain safety, resulting in increased energy consumption and operational expenses. The rising demand for electricity to operate these technologies highlighted the necessity for enhanced energy management efficiency. Over time, the difficulties of tunnel maintenance and energy inefficiency underscored the necessity of implementing innovative technologies to enhance energy efficiency and sustainability in the railway sector.

The body of studies on energy consumption and efficiency in railway systems has expanded consistently, as researchers and industry professionals aim to decrease energy usage and operational expenses while improving the overall sustainability of rail networks. Extensive research has examined energy consumption in real-world testing scenarios, including a comparative comparison of several Electric Multiple Unit (EMU) models [1]. This study highlighted the need of choosing appropriate speed and model combinations to minimize energy consumption during stops and starts, hence enhancing the overall efficiency of the railway system. Likewise, other research has utilized energy consumption analysis, simulation models, and optimization algorithms to enhance the energy efficiency of rail systems [2]. These methodologies underscore the necessity of distinguishing between traction energy, utilized for vehicle propulsion, and non-traction energy, employed for station and tunnel illumination. This difference assists in pinpointing opportunities for energy savings, hence enhancing overall operational efficiency.

Recent research has concentrated on enhancing energy efficiency in railway systems through the utilization of innovative technologies and operational tactics. A 2023 study on the implementation of regenerative braking technology in the Barcelona subway system illustrated that energy produced from braking trains can be transformed into electricity to supply both trains and station equipment, resulting in a 6% reduction in energy consumption and highlighting the potential for energy conservation in urban rail systems [3]. The implementation of smart grid technology and automation in energy management for railway systems has been investigated. A 2024 research on Eastern Railway in India detailed notable energy conservation strategies, including energy regeneration by locomotives, leading to considerable fuel savings and overall reductions in operational costs [4].

Other significant developments are the ongoing adoption of green energy initiatives by Indian Railways, which aspires to achieve net-zero carbon emissions by 2030. As of 2024, Indian Railways has exceeded 238 MW of solar energy capacity, supplying renewable energy to over 1,950 stations, representing a notable advancement in sustainable rail travel. Moreover, energy consumption management in tunnels, where lighting is maintained for safety reasons, has incorporated AI-driven predictive maintenance models and automated lighting systems. These systems optimize energy utilization by activating illumination solely when required, thereby markedly decreasing electricity consumption [5].

Recent studies have documented the effective incorporation of energy-efficient lighting systems and AI-driven infrastructure monitoring into railway tunnels. These systems modulate illumination settings according to real-time ambient circumstances, enhancing energy savings, prolonging equipment lifespans, and reducing maintenance expenses [6]. Subsequent research investigated the effects of energy losses in railway vehicles and their influence on energy-efficient train control. A study introduced various model tiers, each increasingly enhancing realism to mimic energy losses in train operations [7]. These realistic energy loss models have shown considerable promise in improving energy efficiency; however, their broader application poses challenges. In conjunction with these improvements, the utilization of artificial intelligence (AI) in railway infrastructure has increased, with numerous studies investigating techniques such as neural networks, metaheuristics, regression analysis, and fuzzy logic to enhance railway operations [8]. These AI methodologies have demonstrated efficacy in optimizing train scheduling, traffic management, and infrastructure surveillance, markedly augmenting system safety and operating efficiency.

Significant advancements have been achieved in enhancing energy efficiency within tunnel lighting systems. The intelligent adaptive tunnel lighting system, as presented in recent studies by Musa, et al. [9] modulates lighting levels according to real-time conditions to guarantee appropriate illumination while reducing energy usage. This method has been recognized as exceptionally effective in improving safety and energy efficiency in tunnels while decreasing operational expenses. The creation of hybrid lighting systems that integrate natural light with LED-based artificial illumination provides an additional method for decreasing energy usage in tunnel applications. These hybrid systems achieve a balance between energy efficiency and illumination quality, resulting in substantial enhancements in sustainability. Furthermore, studies examining different control systems for tunnel illumination utilizing SCADA technology have shown optimal and economical solutions for both new tunnel constructions and the enhancement of existing tunnels [10]. Despite budgetary limitations, these investigations have provided significant insights into the retrofitting and optimization of tunnel lightin g systems.

The emphasis on urban rail networks has also catalyzed progress in energy efficiency. Research utilizing simulated annealing and multi-parameter approaches to enhance train running curves has indicated possible energy savings of up to 11.2% [11]. These enhancements foster more sustainable urban rail systems, augmenting schedule efficiency and passenger comfort. Additional research has examined energy consumption patterns in railway signal boxes through statistical correlation methods, showing temperature and day length as significant determinants of energy usage [12]. This indicates the possibility of more customized energy management solutions, enhancing efficiency in the railway sector.

Finally, enhancements in rail vehicle technologies, including optimized aerodynamics, have been identified as significant factors in decreasing energy usage in contemporary trains [13]. These developments possess the capacity to markedly reduce operational expenses and emissions, facilitating the shift towards sustainable transportation systems. The amalgamation of technical advancements, such as AI integration, geofencing, cloud automation, and energy-efficient lighting systems, illustrates the revolutionary capacity of contemporary technologies to realize a sustainable and energy-efficient railway infrastructure [14]. The literature indicates that ongoing research and development in these domains is essential for optimizing energy use, minimizing environmental effects, and improving cost-efficiency in the railway industry. Current railway tunnel systems predominantly depend on fundamental automation methods, like motion sensors and load cells, for lighting regulation. These technologies, although efficient in somewhat diminishing energy use, do not incorporate advanced automation techniques such as cloud-based systems and AI-driven predictive maintenance. This deficiency constrains the system's capacity to optimize operations, minimize downtime, and attain substantial cost efficiency. An in-depth examination of present tunnel operations reveals that the energy consumption for the initial 51 tunnels is 76.10 gigawatts, resulting in power expenses of almost 1266.41 million. Nonetheless, current methods concentrate just on lighting optimization, overlooking wider energy management prospects that could furthermore decrease energy consumption to 22.19 gigawatts and expenses to 369.37 million. Furthermore, these technologies inadequately address environmental consequences in a comprehensive manner, including the reduction of carbon footprints and the enhancement of air quality in tunnel environments. The absence of connection with other intelligent transportation systems further reduces the potential for improving overall operating efficiency and sustainability in railway infrastructure.

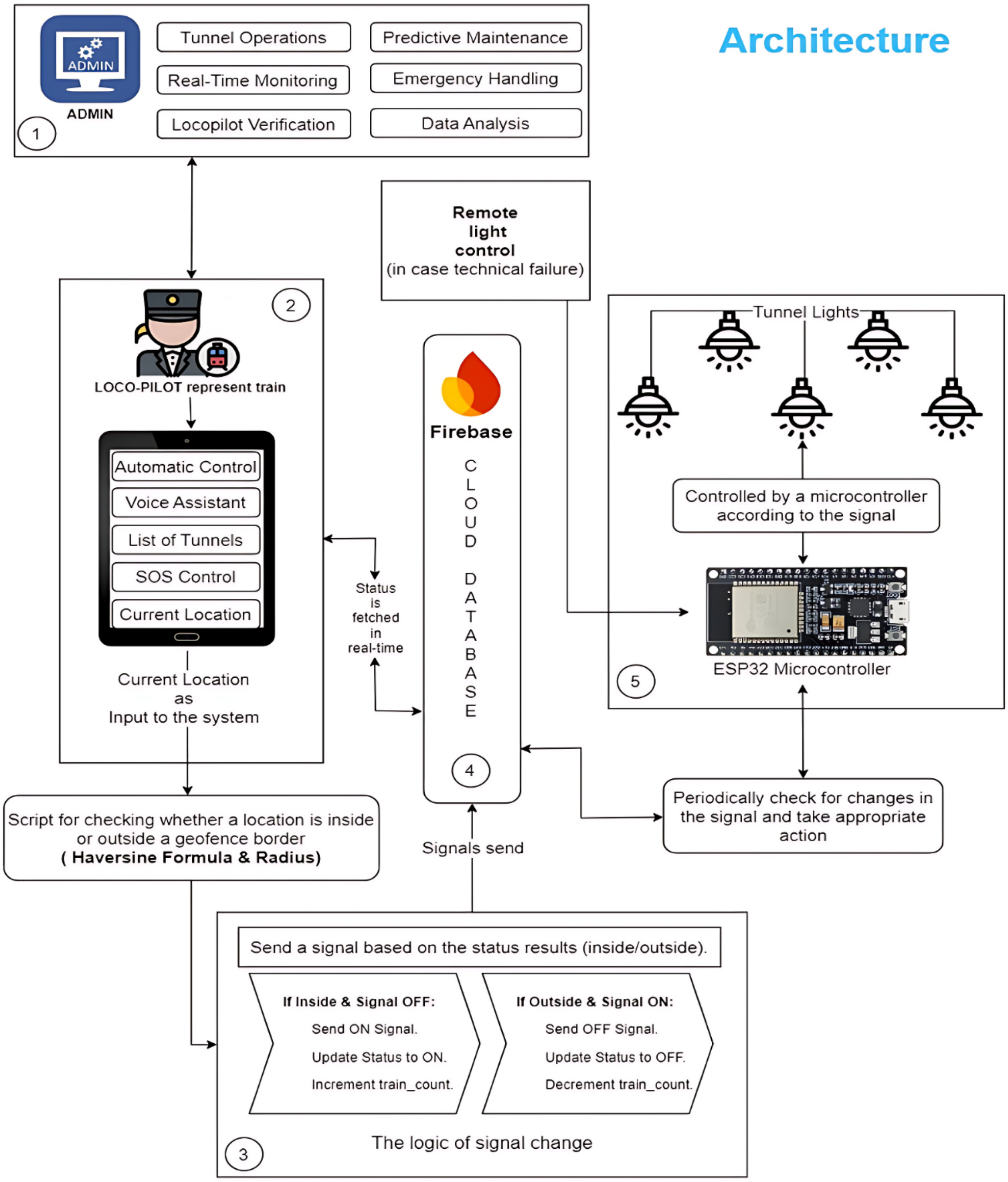

Figure 1.
System Architecture of Proposed System.

3. Proposed Methodology

This proposed methodology presents a novel approach for automated tunnel lighting regulation utilizing real-time train location information. The technology integrates geofencing, cloud connectivity, and microcontroller-based management, guaranteeing an optimal equilibrium between energy savings and operational safety in railway tunnel illumination. The technique employs a Loco Pilot Device (LPD), a cloud-based database, an ESP32 microcontroller, and an Admin Panel for centralized oversight and management.

3.1. 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 ESP32 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 entire 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, so reducing energy consumption while ensuring safety for passengers and operators.

3.2. Locomotive Pilot Device (LPD) with Geofencing

The Loco Pilot Device is a portable, intuitive interface that delivers real-time operational information to the train operator. It perpetually tracks the train's whereabouts utilizing geolocation methods. The device utilizes geofencing to precisely 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.

The Haversine equation is utilized to calculate the distance between the user's current location and the geofences surrounding the tunnel.

$$a = \sin^2\left(\frac{\Delta\phi}{2}\right) + \cos(\phi_1)\cdot\cos(\phi_2)\cdot\sin^2\left(\frac{\Delta\lambda}{2}\right) \quad (1)$$

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

$$d = R\cdot c$$

where:

- d: The distance between the two points.
- R: The radius of the sphere (for Earth, approximately 6371 km or 3958.8 miles).
- $\phi1, \phi2$: Latitudes of the two points (in radians).
- $\lambda1, \lambda2$: Longitudes of the two points (in radians).
- $\Delta\phi = \phi2 - \phi1$: Difference in latitude.
- $\Delta\lambda = \lambda2 - \lambda1$: Difference in longitude.
- $atan2(y, x)$: 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 usage. The LPD incorporates an SOS button and hands-free voice operation, allowing the train operator to execute emergency operations swiftly during atypical circumstances.

3.3. 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 ESP32 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 ESP32 to activate the lights; conversely, upon the train's departure, the ESP32 receives an order to deactivate the lights. A fail-safe mechanism is incorporated into the ESP32 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.

3.4. 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.

3.5. 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 AI-driven 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.

3.6. System Workflow

The system's operational flow comprises several essential steps:

Position Detection: The LPD employs geolocation methods to ascertain the train's position and refreshes 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 ESP32 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.

4. Expected Outcome

The suggested advanced solution aims to transform energy efficiency and operational cost management in 51 Indian railway tunnels through dynamic lighting control utilizing geofencing and cloud automation. The technology conserves energy and upholds safety regulations by activating and disabling lights according to real-time train positions. The solution is augmented with real-time diagnostics, remote monitoring, and predictive maintenance, guaranteeing dependable operations and efficient tunnel management. This novel method diminishes the environmental impact of the railway network while conforming to sustainability objectives, providing a scalable and economic framework for infrastructure modernization.

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

Tunnel Name	No. of Bulbs used	Before Innovation Energy Consumption (Unit)Per Year	After Innovation Energy Consumption (Unit)Per Year	Energy Saved After Innovation (Unit) Per Year
Tike (T-39)	676	1480440	431795	1048645
Patalpani Rail Tunnel	680	1489200	434350	1054850
Nathuwadi (T-6)	718	1572420	458622.5	1113797.5
Maliguda Tunnel	723	1583370	461816.25	1121553.75
Karbude (T-35)	1000	2190000	638750	1551250
Malekhara	1000	2190000	638750	1551250
Rapuru (P-4)	1019	2231610	650886.25	1580723.75
Thane Creek Tunnel	1067	2336730	681546.25	1655183.75
Sangaldan tunnel	1080	2365200	689850	1675350
Trivandrum Port Tunnel	1336	2925840	853370	2072470
Teestabazar (T-16)	1336	2925840	853370	2072470
Keylong Tunnel	1336	2925840	853370	2072470
Pir Panjal railway tunnel	1628	3565320	1039885	2525435
Kalijhora Tunnel (T-13)	1628	3565320	1039885	2525435
Saheilbung tunnel (T -12)	1674	3666060	1069267.5	2596792.5
Tunnel T50	1836	4020840	1172745	2848095
Devprayag Rail Tunnel	2147	4701930	1371396.25	3330533.75

The table presents a comparison of energy consumption for different tunnels prior to and following the deployment of the suggested energy-efficient lighting system. In the Tike (T-39) tunnel, which employs 676 bulbs, the yearly energy usage decreased markedly from 1,480,440 units to 431,795 units, yielding an annual energy savings of 1,048,645 units. This chart illustrates the significant decrease in energy consumption attained by the advanced lighting system, which enhances tunnel illumination through geofencing and real-time train tracking. The findings underscore the system's capacity to minimize energy waste while upholding safety standards, thereby facilitating operational cost reductions and advancing sustainability objectives. These reductions are especially vital in extensive railway networks, where aggregated savings across numerous tunnels can yield substantial environmental and economic benefits, in accordance with global energy efficiency and carbon reduction goals. The chart highlights the feasibility and scalability of the proposed method, providing a standard for future applications.

4.1. Assumptions

- Length of Tike Tunnel: 4.077 km
- Length of Train: 1 km
- Total Distance to Cross the Tunnel: 4.077 km+1 km=5.077
- Speed of Train: 50 km/hr
- Time to Cross Tunnel: Time= (5.077 km / 50 km/hr)×60 minutes=6.1 minutes

4.2. 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, we need to consider that the bulbs are placed 15 meters apart on each side of the tunnel.
Length of Tike Tunnel: 5.077 km, so the total length of the tunnel for both sides (for bulb placement) is:
Total Length = 5.077 km×2=10.154 km=10,154 meters
Total Number of Bulbs = 10,154 meters/15 meters = 676 bulbs

4.3. Energy Consumption Before Innovation

Total Power Consumption per Hour (Before Innovation): Power Consumption per Hour = 676 bulbs×250 W = 169 unit /hr
Energy Consumption per Day (Before Innovation): 169 units/hr×24 hrs=4,056 units/day
Energy Consumption per Month (Before Innovation): 4,056 units/day×30 days=121,680 units/month
Energy Consumption per Year (Before Innovation): 4,056 units/day×365 days=1,480440 units/year

4.4. Energy Consumption after Innovation (For 7 Busy Hours)

Power Consumption per Day=169 unit /hr×7 hrs=1,183 unit /day
Energy Consumption per Month (After Innovation): 1,183 units/day×30 days=35,490 units/month.
Energy Consumption per Year (After Innovation): 1,183 units/day×365 days=431795 units/year.

4.5. Energy Savings After Innovation

Energy Savings per Year = 1,480440 units/year − 431795 units/year = 1,048645 units/year.

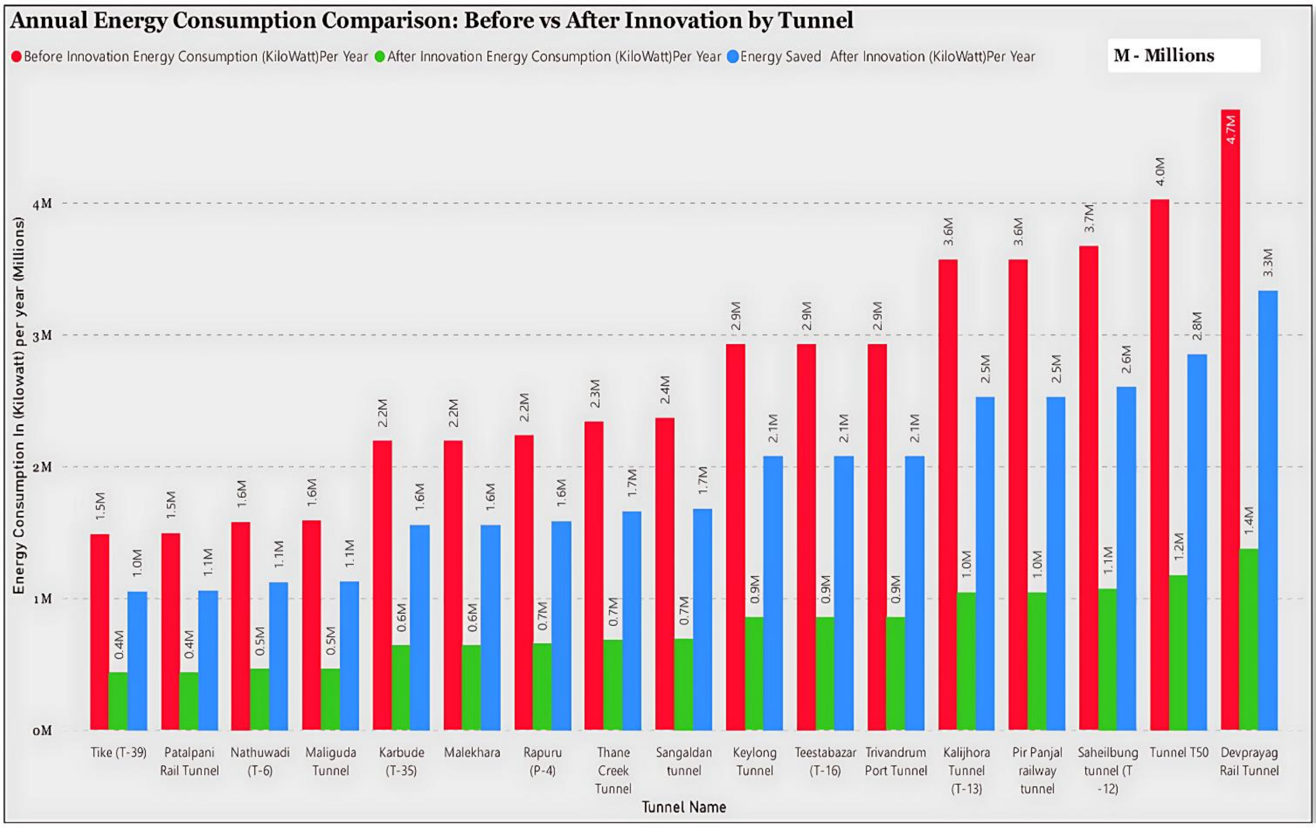

Figure 2.
Energy Consumption Visualization: Pre- and Post-Innovation Impact.

Figure 2 presents a comprehensive comparison of annual energy usage for different tunnels, prior to and subsequent to the adoption of energy-efficient improvements. The chart features three unique bars for each tunnel: the red bar denotes energy consumption prior to the invention, the green bar indicates energy consumption subsequent to the innovation, and the blue bar illustrates the energy savings achieved due to the innovation. Energy usage is quantified in millions of units annually, facilitating a clear and measurable assessment of the advancements attained. The considerable decrease in energy use, illustrated by the green bars being significantly lower than the red bars, underscores the beneficial effect of the novel energy management system. The energy conserved, depicted in blue, illustrates the system's operational efficiency while also aiding in the reduction of operational expenses, fostering sustainability, and lessening the environmental impact of tunnel operations throughout the railway network. This visual depiction robustly substantiates the efficacy of the advances in improving energy efficiency across the tunnels.

Table 2.
Maintenance Cost Analysis Over 4 Years.

Tunnel Name	No. of Bulbs used	Length of Tunnel (Km.)	Before Innovation Maintenance Costing (Million Rupees) Per 4 Year	After Innovation Maintenance Costing (Million Rupees) Per 4 Year
Tike (T-39)	676	4.07	1892800	473200
Patalpani Rail Tunnel	680	4.1	1904000	476000
Nathuwadi (T-6)	718	4.38	2010400	502600
Maliguda Tunnel	723	4.42	2024400	506100
Karbude (T-35)	1000	6.5	2800000	700000
Malekhara	1000	6.5	2800000	700000
Rapuru (P-4)	1019	6.64	2853200	713300
Thane Creek Tunnel	1067	7	2987600	746900
Sangaldan tunnel	1080	7.1	3024000	756000
Trivandrum Port Tunnel	1336	9.02	3740800	935200
Teestabazar (T-16)	1336	9.02	3740800	935200
Keylong Tunnel	1336	9.02	3740800	935200
Pir Panjal railway tunnel	1628	11.21	4558400	1139600
Kalijhora Tunnel (T-13)	1628	11.21	4558400	1139600
Saheilbung tunnel (T - 12)	1674	11.55	4687200	1171800
Tunnel T50	1836	12.77	5140800	1285200
Devprayag Rail Tunnel	2147	15.1	6011600	1502900

Table 2 presents a comparison of the total maintenance costs for the tunnel lighting system over a four-year period, both before and after the implementation of the innovative energy-saving measures. Using the Tike (T-39) Tunnel as an example, the table highlights the significant reduction in maintenance costs following the introduction of the innovation. Prior to the innovation, the maintenance costs were considerably higher, reflecting the inefficiencies of the older system. However, after the innovation, these costs decreased, demonstrating the positive impact of the new energy-efficient lighting system. This reduction in maintenance costs underscores the financial benefits of the innovation, contributing to long-term savings and improving the overall cost-effectiveness of tunnel operations.

4.5. Before Innovation

Maintenance Cost per Bulb: ₹700
Number of Bulbs: 676
Total Cost for 1 Year: ₹700 × 676 = ₹472,800
Total Cost for 4 Years: ₹472,800 × 4 = ₹18,928,000

4.6. After Innovation

Maintenance Cost per Bulb: ₹700 (same as before)
Number of Bulbs: 676
Total Cost for 4 Years (After Innovation): ₹700 × 676 = ₹472,800

The usage of bulbs will be reduced after the innovation, leading to an increase in the lifespan of the bulbs. As a result, the maintenance cost will also decrease.

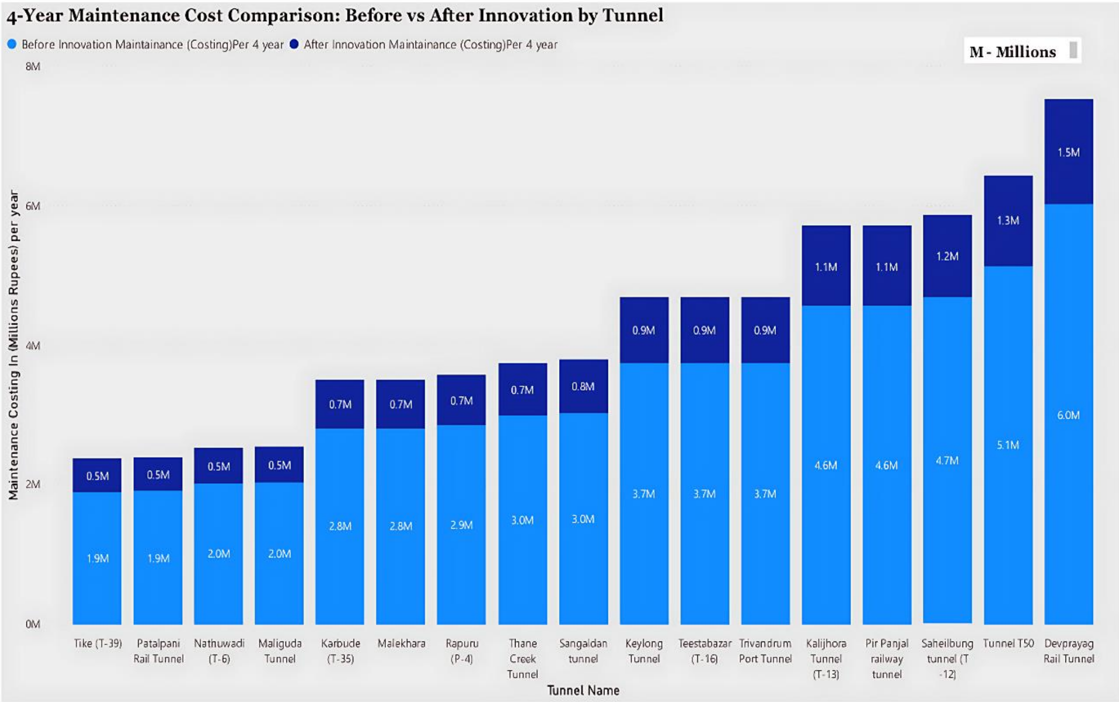

Figure 3.
Visualization of Maintenance Cost Analysis Over 4 Years.

Figure 3 illustrates the comparison of maintenance expenses prior to and after the deployment of the innovation overa four-year duration. Before the innovation, maintenance expenses for some tunnels were significantly elevated, with Tunnel T-50 incurring charges as high as 6.0 million rupees. Following the implementation of the energy-efficient lighting system, a notable decrease in maintenance expenses was observed in numerous tunnels. In several instances, expenses diminished by up to 1.5 million rupees or more, demonstrating the significant financial savings resulting from the innovation. This reduction highlights the innovation's efficacy in optimizing long-term maintenance costs and enhancing the overall sustainability of tunnel operations.

Table 3.
Cost Savings Across Tunnels.

Tunnel Name	Length of Tunnel (Km.)	Costing Saved After Innovation (Rs) Per Year
Tike (T-39)	4.07	17449452.8
Patalpani Rail Tunnel	4.1	17552704
Nathuwadi (T-6)	4.38	18533590.4
Maliguda Tunnel	4.42	18662654.4
Karbude (T-35)	6.5	25812800
Malekhara	6.5	25812800
Rapuru (P-4)	6.64	26303243.2
Thane Creek Tunnel	7	27542257.6
Sangaldan tunnel	7.1	27877824
Trivandrum Port Tunnel	9.02	34485900.8
Teestabazar (T-16)	9.02	34485900.8
Keylong Tunnel	9.02	34485900.8
Pir Panjal railway tunnel	11.21	42023238.4
Kalijhora Tunnel (T-13)	11.21	42023238.4
Saheilbung tunnel (T -12)	11.55	43210627.2
Tunnel T50	12.77	47392300.8
Devprayag Rail Tunnel	15.1	55420081.6

Table 3 provides a comprehensive comparison of energy use and related expenses prior to and subsequent to the innovation in the Tike Tunnel (T-39). The data indicates a substantial decrease in energy usage and operational costs after the installation of the energy-efficient lighting system. Prior to the innovation, the tunnel's energy consumption was significantly elevated, resulting in heightened operational expenses. Following the innovation, energy consumption decreased markedly, leading to considerable savings in both energy units and monetary expenses. This illustrates the immediate effect of the invention on diminishing the tunnel's environmental impact and operational costs, so underscoring its efficacy in advancing sustainable and economical railway operations.

4.7. Cost Calculation Before and After Innovation

- Before Innovation: Energy consumption per year = 1,480,440 units
- After Innovation: Energy consumption per year = 431,795 units
- Cost per unit of energy = ₹16.64

4.8. Before Innovation (Energy Cost)

Energy Cost = 1,480,440 units × 16.64 = ₹ 24,634,521.6

4.9. After Innovation (Energy Cost)

Energy Cost=431,795 units × 16.64 = ₹7,185,068.8

Energy Savings After Innovation: ₹24,634,521.6 - ₹7,185,068.8 = 17,449,452.8

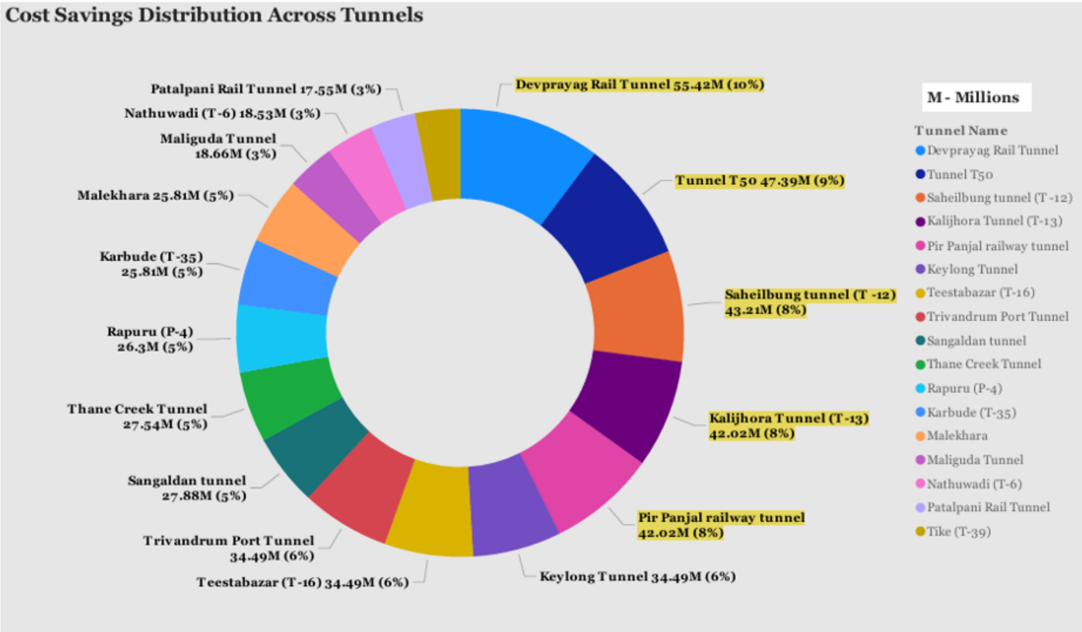

Figure 4.
Visualization of Cost Savings Across Tunnels

Figure 4 depicts the allocation of cost reductions among several tunnels, quantified in millions (M), displayed in a circular chart manner. The diagram distinctly illustrates the substantial savings realized by particular tunnels, with the Devprayag Rail Tunnel yielding the most at 10%, followed closely by Tunnel T-50 at 9%. Minimal savings are noted in tunnels such as the Patalpani Rail Tunnel and Nathuwadi, both yielding approximately 3%. The color-coded segments of the chart facilitate the distinction between the tunnels, while the accompanying legend enhances comprehension of the data. This graphic clearly illustrates the extent to which the invention has resulted in diverse cost savings across several tunnels, highlighting its significant influence on energy efficiency and operational cost reduction.

5. Conclusion

The proposed system presents an innovative solution to enhance energy efficiency and sustainability in railway tunnel operations. By leveraging smart technology to control lighting based on train proximity and incorporating AI-driven predictive maintenance, the system significantly reduces energy consumption, along with operational and maintenance costs. A comprehensive analysis of the first 51 tunnels reveals that the current energy consumption amounts to 76.10 gigawatts, resulting in electricity costs of approximately 1266.41 million rupees. After the implementation of the proposed solution, energy consumption can be reduced to 22.19 gigawatts, thereby cutting electricity costs to just 369.37 million rupees. This substantial reduction not only decreases operational expenses but also minimizes the environmental impact, contributing to a more sustainable railway infrastructure. The integration of these advanced technologies streamlines operations, supports the transition toward greener transportation solutions, and sets the stage for a future of more efficient, environmentally friendly, and cost-effective railway systems, benefiting both the sector and society at large.

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