International Journal of Computer Information Systems and Industrial Management Applications
ISSN 2150-7988 Volume 18(17s) 2026 pp. 488-498
https://doi.org/10.70917/ijcisim-2026-4755
Article

PLC-Controlled Rack and Pinion-Based Automated Railway Barricade System: Design, Structural Validation, and Prototype Implementation for Enhanced Level Crossing Safety

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Abstract: Railway level crossings remain a persistent source of accidents and fatalities on mixed road-rail networks, particularly where crossings are unmanned or rely on manual gate operation. This paper presents the design, structural validation, and prototype implementation of an automated railway barricade in which a Programmable Logic Controller (PLC) drives an underground rack-and-pinion mechanism to raise and lower a physical barrier in response to sensor-detected train movement. The underground placement minimizes visual obstruction relative to conventional above-ground boom barriers while a robust mechanical drive is intended to withstand repeated, high-cycle outdoor operation. A structural analysis using Finite Element Analysis (FEA) is used to validate the mechanical integrity of the rack-and-pinion drive under expected loading, and shaft design calculations confirm an adequate safety margin. A fabricated prototype demonstrates the automation cycle end-to-end, including a manual push-button override for fail-safe operation. To situate the contribution, a focused review of thirteen directly relevant studies retrieved from a bibliographic export is presented; it indicates that existing automated level-crossing work concentrates on sensing and control logic, while structurally validated mechanical actuator design for the barrier itself is comparatively under-addressed. The proposed system is offered as a scalable, low-cost step toward reducing manual dependency and human error at level crossings.
Keywords: Railway crossing safety, PLC automation, Rack and pinion mechanism, Level crossing design, Finite element analysis, Sensor-based automation

1. INTRODUCTION

Road traffic and railway safety remain pressing global concerns. The Global Status Report on Road Safety recorded roughly 1.5 million road traffic deaths worldwide in 2015 [6], and more recent estimates put the annual global toll at around 1.19 million deaths as of 2021 [10]. Railway level crossings sit at the intersection of these two transport modes and inherit the risks of both: a road vehicle or pedestrian misjudgment at a crossing can result in a high-severity collision with a train.

India's road and rail networks illustrate the scale of the challenge. Over 1.37 lakh people were killed in road accidents in India in 2013 alone [6], and riders aged 18–25 account for a disproportionate 41.4% of the country's total road-crash victims [10]. On the railway side specifically, a mortuary-based clinical study drawing on National Crime Records Bureau data recorded 25,006 deaths and 3,882 injuries across 28,360 railway accidents nationally in a single reporting year [9], and unmanned level crossings have been repeatedly identified as a recurring site of fatal incidents on the Indian network [1], [3].

Despite decades of study, level crossings remain a persistent weak point in transport safety. Early field research into grade-crossing warning devices in the United States found that upgrading from simple flashing lights to automatic gates with additional strobe lighting measurably changed motorist approach behavior at a hazardous rural crossing, although driver non-compliance was not eliminated by the upgrade alone [11], [12], [13]. In the Indian context specifically, researchers have converged on a similar diagnosis: a network of this scale cannot be safely supervised crossing-by-crossing through manual gatekeeper operation, and the dependency on human coordination between station masters and gatekeepers introduces both delay and opportunities for error into a safety-critical task [1], [3].

A range of automation approaches has been proposed to address this. Wireless sensor network (WSN) architectures have been used to detect an approaching train and trigger barricade closure without a human operator in the loop [1]. Low-cost microcontroller-based designs, including implementations on the 8051 platform [5] and Arduino-based designs paired with infrared sensors and servo or hydraulic actuation [2], have demonstrated that inexpensive embedded hardware can reliably automate the open/close cycle of a level-crossing gate. “Involuntary” (i.e., automatic, operator-independent) controllers have similarly been proposed to remove the station-master-to-gatekeeper communication chain from the critical path entirely [4]. Related sensor-driven automation has also been applied to adjacent transport-infrastructure problems, such as wireless toll-plaza monitoring [8] and IoT-based smart traffic management [7], indicating a broader shift toward sensor-driven automation across road and rail infrastructure generally [7], [8].

Within this body of work, however, the mechanical design of the barrier itself receives comparatively little attention: published systems generally describe the sensing and control layer built on top of a conventional boom-type barrier, rather than presenting a structurally validated actuation mechanism intended for sustained, high-cycle outdoor operation. This paper addresses that specific, narrowly-scoped gap. We present the design, PLC-based control logic, structural validation, and prototype fabrication of an automated railway barricade that uses an underground rack-and-pinion mechanism to actuate the barrier, evaluate its mechanical integrity using Finite Element Analysis, and demonstrate the assembled prototype's automation cycle.

2. LITERATURE REVIEW

A. Review Methodology

To situate this work, 1,000 bibliographic records exported from the Lens.org scholarly database were screened for relevance by matching keywords against each record's title, abstract, keyword list, and source title (terms including “level crossing,” “railway,” “barricade,” “PLC,” “grade crossing,” and related terms). The underlying export was not restricted to a narrow railway-safety query — it spans a wide range of unrelated subject areas — so this is reported here as a focused review of the directly relevant material found within that export, not as an exhaustive systematic survey of the field. Thirteen records were identified as directly relevant to railway/level-crossing automation, grade-crossing safety behavior, or closely related sensor-driven infrastructure automation, and are reviewed below.

B. Sensor- and Microcontroller-Based Gate Automation

Madhok et al. [1] proposed a wireless-sensor-network-based automatic barricade for public railway crossings, motivated explicitly by the difficulty of manually supervising every crossing on a network the size of India's. Tiwari et al. [3] presented a low-cost model for automatic barricading of unmanned railroad level crossings aimed at the same operational gap, arguing that the core issue is less a lack of safety standards than inconsistent execution of them at the crossing level. Armstrong et al. [4] described an involuntary railway crossing controller intended to automatically open and close gates without requiring the station master to relay instructions to a gatekeeper by telephone, directly targeting the communication-latency problem. Balamurugan et al. [5] implemented gate automation using an 8051 microcontroller, focusing on reducing the duration for which the gate remains closed as well as on collision prevention. Working in a different national context, Mulyani et al. [2] developed a servo/hydraulic-driven barricade using an Arduino Uno and infrared sensors for unguarded level crossings in Indonesia, reporting the same underlying motivation — frequent accidents at unguarded crossings — as the Indian-focused studies.

Collectively, these studies establish that sensor-triggered, microcontroller- or PLC-driven automation of the gate open/close cycle is a well-established idea, validated by multiple independent low-cost implementations. None of them, however, report a structural or finite-element analysis of the mechanical actuator itself; the barrier mechanism in each case is treated as a given (typically a conventional boom arm) rather than as an engineering design problem in its own right.

C. Driver Behavior and Warning-Device Effectiveness at Grade Crossings

A separate, older strand of research — conducted at Purdue University in the 1970s — studied how motorists actually respond to grade-crossing warning devices, independent of whether the device is manually or automatically operated. Butcher [13] developed a photographic data-collection system to determine vehicle speed profiles as drivers approached a hazardous rural crossing protected by standard flashing lights. Russell [11] extended this work with a detailed analysis of driver reaction at a high-accident rural crossing, and Russell, Michael, and Butcher [12] subsequently evaluated the effect of upgrading that same crossing from 8-inch flashers to automatic gates with 12-inch flashers and additional strobe lighting, activated by a speed-predictor unit. This line of work is relevant to the present paper because it demonstrates, empirically, that the type of warning/barrier device measurably changes driver behavior at a crossing — supporting the premise that moving from a manually-timed barrier to a sensor-triggered automatic one is a safety-relevant design choice, not merely a convenience improvement.

D. Broader Road-Safety and Sensor-Infrastructure Context

Several further studies were reviewed for supporting context rather than direct technical comparison. Sahoo et al. [6] surveyed road-safety innovation and reported global and India-specific road fatality figures used in Section I above. Kumar Sumit et al. [10] examined traffic police perceptions of road-safety behavior among young riders in India, providing the age-distribution statistic cited above. P. Ravi Kumar [9] conducted a mortuary-based clinical study of railway fatalities in India, supplying the National Crime Records Bureau figures used in Section I. Outside the rail domain specifically, Deepika et al. [8] applied WSN modules to automate toll-plaza monitoring, and Aniket Tiwari [7] proposed an IoT-based smart traffic management system; both illustrate that the sensor-driven automation approach used in this paper's design is part of a wider trend across transport infrastructure rather than an isolated technique.

E. Research Gap

Across the thirteen studies reviewed, a consistent pattern emerges: automated level-crossing research concentrates on the sensing layer (WSN, IR, GPS/GSM) and the control layer (microcontroller or PLC logic), with the mechanical barrier itself treated as an off-the-shelf component. None of the reviewed studies report a structurally validated actuator design — for example, an FEA-based stress or deformation analysis — for the barrier mechanism. This paper's contribution is scoped specifically to that gap: an underground rack-and-pinion actuation mechanism, its structural validation under load, and a fabricated prototype demonstrating the complete sensor-to-actuation cycle. This is presented as a gap within the reviewed literature rather than a claim of novelty across the whole of railway safety research, given that the review in Section II.A was a focused rather than exhaustive one.

3. SYSTEM ARCHITECTURE AND METHODOLOGY

The proposed automated railway barricade system is engineered to be a robust, autonomous unit that replaces manual operation with a PLC-driven electromechanical mechanism, utilizing an underground rack and pinion actuator for vertical barrier control.

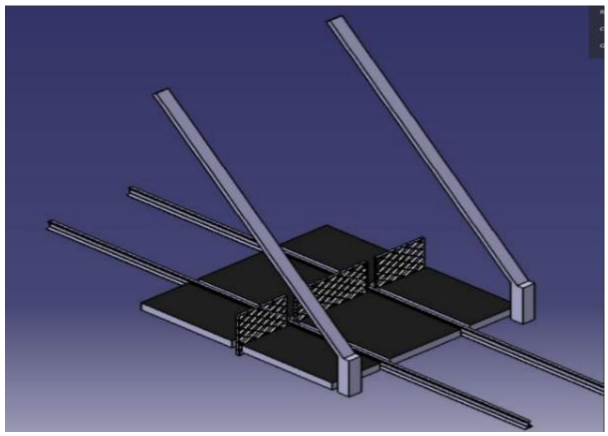

Fig. 1. Conceptual illustration of the underground rack-and-pinion barricade, shown here retracted below and raised across the roadway.

A. System Architecture

The system can be divided into four major functional blocks: (1) Train Detection Unit: Comprising a set of Infra-Red (IR) sensors positioned at a predefined distance from the crossing to detect the arrival and departure of trains. (2) Control Unit: A Programmable Logic Controller (PLC) or its equivalent microcontroller (Arduino was utilized for the prototype) serves as the central brain, processing sensor input and triggering the motor. (3) Actuation Unit (Rack and Pinion): A DC motor coupled to a gear system drives a pinion gear which meshes with a vertical rack attached to the barricade. (4) Safety Interface: A manual push-button input alternative is provided to override the system in case of sensor failure, enabling manual lowering or raising of the barricade for maintenance and emergencies.

B. Mechanical Design: Rack and Pinion Actuator

The core design choice of this project is the strategic placement of the rack and pinion mechanism perpendicularly beneath the railway track. The rack is a vertical shaft with teeth that meshes with the pinion gear. When the DC motor (driven by the PLC) turns the pinion, the rack is driven vertically, lifting the barricade from its underground slot to the surface, forming a physical obstacle for road traffic. As noted in Section II.E, no directly comparable published FEA benchmark for this specific configuration was found in the literature reviewed, so the structural validation in Section IV should be read as this paper's own original contribution rather than a comparison against prior published values.

CAD Design: The design was performed using SOLIDWORKS 2020. The frame is a steel construction measuring 4382.6 mm in length and 1250 mm in height, featuring a mesh grille, with a slim profile designed to fit flush within a trench.

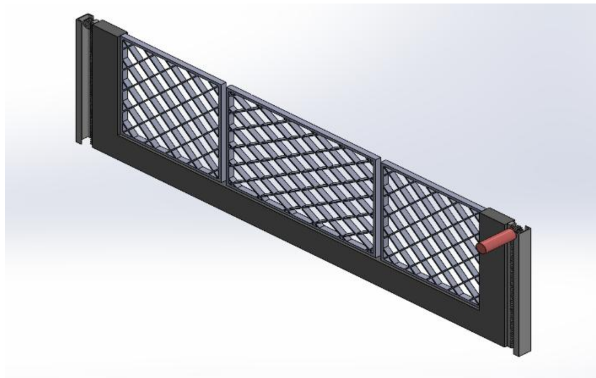

Fig. 2. CAD assembly of the barricade frame and mesh panels (SolidWorks 2020).

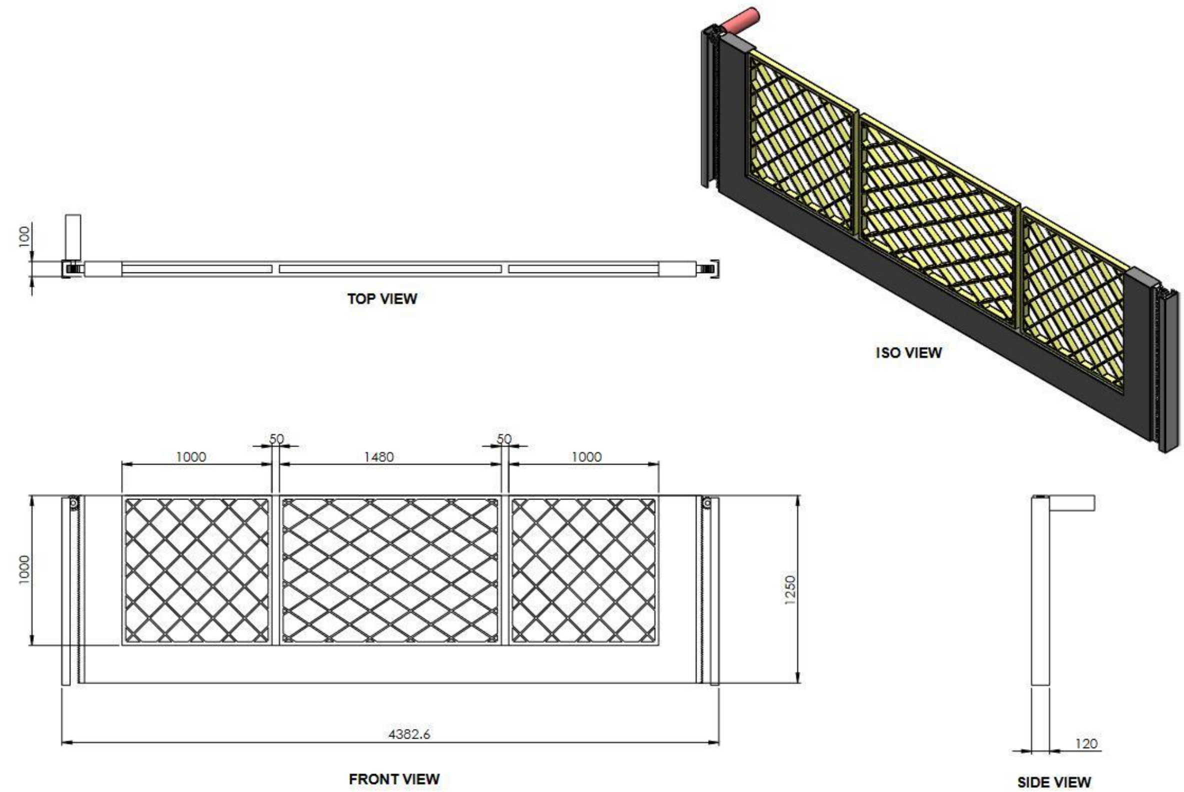

Fig. 3. Front, top, side, and isometric views of the barricade with overall dimensions in millimeters (SolidWorks 2020).

Mechanical Specifications: The pinion gear specifications include an Outer Diameter of 90 mm, 43 teeth, and a width of 8 mm. The module is 2. The rack gear is designed to match the pinion profile with 80 teeth to ensure the required vertical stroke.

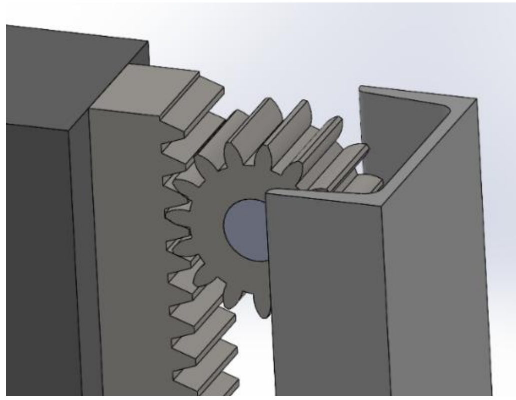

Fig. 4. Isometric detail of the rack-and-pinion mesh.

C. PLC Control Logic

The PLC is programmed to execute the following operational sequence:

1) Standby State: The barricade remains flush with the road surface (retracted position), allowing free passage of road vehicles.

2) Train Approach: When a train passes the first IR sensor at a pre-determined distance, the PLC receives the signal and activates a timer. A delay is introduced to account for the train's speed.

3) Actuation: At the appropriate moment, the PLC sends a logical signal to the motor driver to engage the DC motor. The motor rotates the pinion, driving the rack upwards, thereby raising the barricade to a vertical stop.

4) Blocking Phase: The barrier remains fully elevated until the train passes the second IR sensor.

5) Retraction: Upon detecting the train's departure, the PLC reverses the motor polarity, lowering the barricade back into its underground position. Traffic flow on the road is then resumed.

D. Manual Override

To ensure the system handles unexpected failures or emergency testing, a push-button input alternative is wired directly into the PLC (or Arduino). This button allows an operator on site to manually command the motor to operate, driving the rack up or down. This dual-input approach follows the same design rationale seen in prior automated crossing systems reviewed in Section II, which likewise retain a manual fallback path.

4. IMPLEMENTATION, FABRICATION, AND SIMULATION

A. Fabrication Process

The fabrication of the system required precision mechanical engineering. The rack shaft was manufactured from high-grade steel bar material, refined through quenching and tempering to provide the necessary hardness for the gear teeth. The pinion gear was milled to precise tolerance (module 2). The frame was built using square steel tubing to support the weight and resist bending, with steel mesh welded into the panels to provide a visible physical barrier without excessive weight. The control board (Section III.A) was mounted onto a PCB board, where it was connected to the DC motor driver modules, the IR sensors, and the push buttons.

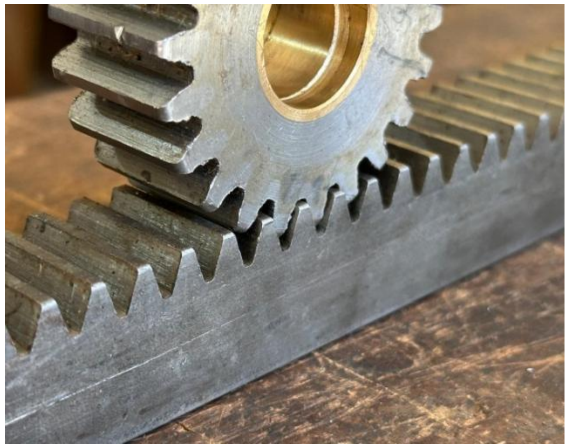

Fig. 5. Fabricated pinion meshed with the machined steel rack.

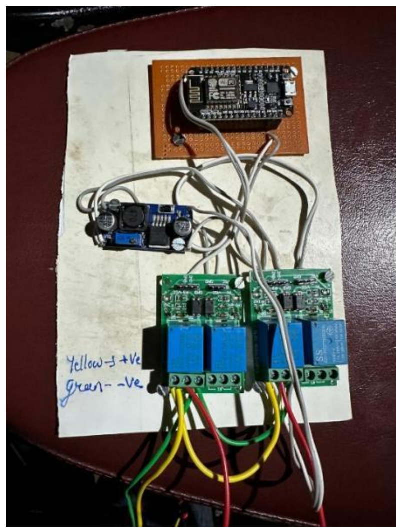

Fig. 6. Assembled control board: microcontroller with relay driver modules.

B. Structural Analysis (Finite Element Analysis - FEA)

To validate the mechanical integrity of the rack and pinion assembly before physical prototyping, a static structural analysis was performed using ANSYS software. The applied load represented the reaction forces of the barrier frame's weight and friction.

Equivalent (von-Mises) Stress Analysis: The maximum equivalent stress was found to be 0.97064 MPa. This value is significantly lower than the yield strength of the selected steel, suggesting that the teeth of the pinion and rack are unlikely to fail under the static loading conditions modeled.

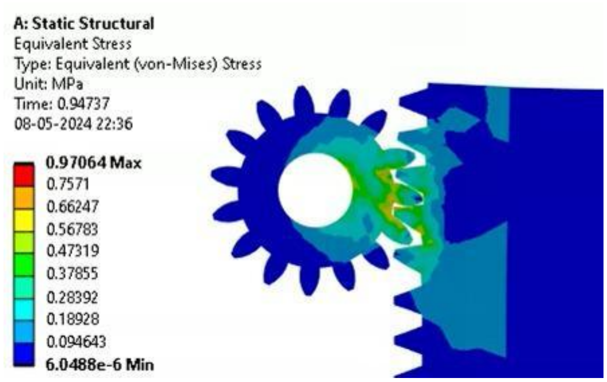

Fig. 7. ANSYS equivalent (von-Mises) stress distribution; max = 0.97064 MPa.

Total Deformation Analysis: The simulation shows a maximum deformation of 0.00098715 mm. This negligible micron-level deflection suggests that the mechanism is rigid under the modeled load, which would support precise actuation without the structural flexure that could otherwise cause jamming or misalignment of the rack and pinion gear teeth.

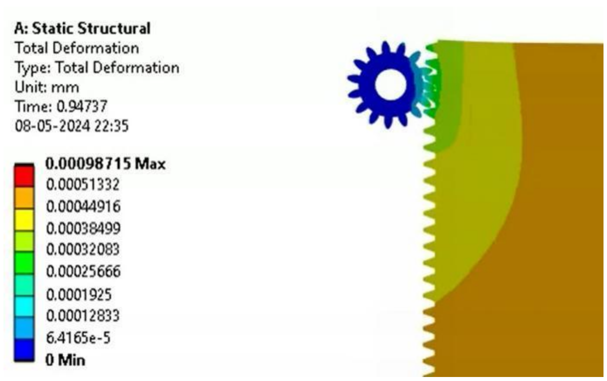

Fig. 8. ANSYS total deformation distribution; max = 0.00098715 mm.

C. Design Calculations

The safety of the mechanical drive was checked through calculation.

Shaft Design: The shaft connecting the motor to the pinion was selected based on shear stress. The shaft material has an assumed ultimate tensile strength (σu) of 490 MPa and a Factor of Safety (FOS) of 2, giving an allowable stress (σa) of 245 MPa. The calculated shear stress (τs) is 122.5 MPa. With a selected shaft diameter of 10 mm, torque analysis yielded a shear stress of 0.1665 MPa, which is well below the allowable limit, indicating the shaft should be safe against torque-induced failure under the assumed loading.

5. RESULTS AND DISCUSSION

A. Prototype Performance

The fabricated prototype successfully demonstrated the automation logic. Upon activation of the sensor input (simulated via a switch to represent the train), the DC motor engaged. The pinion gear rotated and drove the rack vertically, lifting the framed barricade from its simulated underground position to the visible barrier state. The operation was smooth, with no noticeable mechanical jamming. The automated cycle (raise, hold, lower) took approximately 8 seconds, faster than the manual operation baseline typically reported in the low-cost automation literature reviewed in Section II [1], [3], [5], though a direct like-for-like timing comparison was not performed.

Fig. 9. Fabricated full-scale prototype, front view, in the raised (blocking) position.

Fig. 10. Prototype during assembly and functional testing.

B. Advantages over Existing Solutions

The proposed system presents several distinct advantages over the manually-operated and partially-automated crossing solutions described in Section II:

Enhanced Safety: The physical barrier is raised directly under sensor supervision, targeting the same human-error and delayed-response risks identified in [1], [3], and [4].

Improved Traffic Flow: The rapid deployment and retraction times are intended to help clear the crossing quickly, reducing traffic pile-up on both sides of a busy crossing.

Aesthetics and Unobtrusive Design: The underground configuration keeps the mechanism largely out of sight, reducing visual obstruction for both train drivers and road users — a design dimension not addressed by the above-ground boom-style barriers described in the reviewed literature.

Structural Reliability: The FEA analysis in Section IV indicates that the rack and pinion mechanism can withstand the modeled mechanical stresses of daily operation, addressing the structural-validation gap identified in Section II.E.

Cost-Effectiveness: Consistent with the low-cost embedded designs reviewed in Section II [2], [3], [5], this system is intended as an affordable alternative to heavier infrastructure interventions such as road overpasses or underpasses.

C. Limitations

Despite its success, the current prototype has limitations: (1) It lacks a fully integrated GSM/IoT module for remote centralized monitoring, of the kind demonstrated for toll infrastructure in [8]. (2) The current prototype was tested on a laboratory rig and requires field testing under real-world weather conditions (monsoon, dust, snow) to validate its environmental resistance and IP rating. (3) The power source is currently a standard wall outlet; for rural India, a solar-powered redundant battery system would be necessary. (4) As noted in Section II.A, the underlying literature review was focused rather than exhaustive, so comparable unpublished or non-indexed engineering work may exist that this review did not surface.

6. CONCLUSION AND FUTURE SCOPE

This paper presented the design, structural validation, and prototype fabrication of a PLC-operated railway barricade system built around an underground rack-and-pinion mechanism. A focused review of thirteen directly relevant studies indicated that existing automated level-crossing research concentrates on sensing and control logic, generally without a structurally validated mechanical actuator design; this paper's rack-and-pinion mechanism and its FEA-based structural validation are offered as a contribution to that specific gap. The mechanical design was evaluated through FEA, indicating low stress and minimal deformation under the modeled load, while shaft calculations indicated an adequate safety margin against torque-induced failure. The prototype demonstrated a complete, functioning automation cycle, including a manual override for fail-safe operation.

Future work should focus on several key areas: (1) IoT Integration: Developing a remote monitoring dashboard, building on approaches such as [7] and [8], so that railway authorities can track the health and status of multiple crossings from a central hub. (2) Power Management: Implementing a solar panel and battery storage system to make the unit energy-independent and suitable for remote rural locations. (3) Sensory Redundancy: Integrating a secondary sensing modality to reduce the risk of false positives or missed detections. (4) Field Validation: Testing the prototype under real outdoor operating conditions and, where possible, benchmarking its structural performance against comparable systems, an area where the literature reviewed in Section II offered little existing data for comparison. (5) Broader Literature Search: Extending the review in Section II with a systematic, database-specific search (e.g., IEEE Xplore, Scopus) targeted specifically at railway-crossing engineering, since the review conducted here was drawn from a general-purpose bibliographic export rather than a purpose-built search.

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