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Integrating Wireless Sensor Networks and Machine Learning for Proactive Safety and Operational Risk Management on the Addis Ababa–Djibouti Transport Corridor

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Abstract:
The Addis Ababa–Djibouti corridor serves as Ethiopia's economic lifeline, handling approximately 95% of the nation's international trade. Despite its strategic importance, the corridor faces significant safety and operational challenges, with heavy goods vehicles involved in 6,914 crashes (14.85% of the total) in 2024, resulting in 715 fatalities. Railway operations are constrained by outdated signaling systems, limiting capacity to only two trains between stations. This study develops an integrated framework combining wireless sensor networks (WSNs) and machine learning for proactive safety monitoring and operational risk management along the corridor. The methodology employs a multi-tier WSN architecture with edge and cloud computing, utilizing gravitational search algorithms for optimal node placement. Machine learning models, Random Forest, XGBoost, and LightGBM, were trained on 2,000 accident records (2018–2023), with SMOTE addressing class imbalance. Random Forest achieved 82% accuracy (AUC-ROC: 0.87), identifying driver age (mean 44 years), nighttime on unlit roads (+62% fatal probability), and rainy conditions as key severity predictors. The proposed WSN-based railway signaling enables 3–4 trains to operate between stations simultaneously, representing a 50–100% capacity increase. Integration of sensor networks and ML enables a fundamental shift from reactive to proactive risk management, with estimated benefits including 15–25% accident reduction, 20–30% maintenance cost savings, and 15–25% extension of infrastructure lifespan. The framework directly aligns with the World Bank's USD 500 million, Regional Economic Corridor Project and offers a scalable, replicable model for deploying intelligent transport systems across developing economies. This research contributes the first integrated sensor-ML framework for an African trade corridor, offering practical evidence for policy formulation and technology investment prioritization.
Keywords:
Wireless Sensor Networks; Machine Learning; Transport Corridor Safety; Ethiopia–Djibouti Trade Route; Predictive Risk Management

I. Introduction

1.1 Background and Context

The Addis Ababa–Djibouti corridor constitutes the economic lifeline of the Federal Democratic Republic of Ethiopia. As a landlocked nation of more than 130 million people (The Reporter Ethiopia, 2026), Ethiopia remains heavily dependent on neighbouring Djibouti for access to international maritime trade routes. The corridor currently handles more than 95% of Ethiopia's imports and exports, making its efficiency critical for the broader economy (TradeMark Africa, 2026). The World Bank confirms that the Addis-Djibouti corridor accounts for 95 percent of the country's import-export trade (World Bank, 2020). By early

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2024, more than 95% of Ethiopia's seaborne trade transited through Djibouti, primarily via the Doraleh port complex (Addis Standard, 2026).

The scale of commerce flowing through this corridor is immense. Imports Global (2024) data shows that at least 90 percent of Ethiopia's international trade passes through the Port of Djibouti, encompassing an import bill estimated at USD 25.9 billion in 2024 and exports of approximately USD 4.89 billion, led by coffee, which accounts for close to 45 percent of Ethiopia's foreign exchange earnings (The Reporter Ethiopia, 2026). For Djibouti, port activity accounts for around 76 percent of the country's GDP, and Ethiopian transit cargo generates an estimated USD 1.5 billion to USD 2 billion in annual revenues through port tariffs and fees, roughly 25 percent of the country's total income (The Reporter Ethiopia, 2026). The International Monetary Fund notes that approximately 95 percent of Djibouti's port activity is fuelled by Ethiopian trade, intimately tying both nations' growth trajectories closely together (The Reporter Ethiopia, 2026).

Complementing the road network, the 752-kilometre electrified railway linking Addis Ababa and Djibouti City stands as Africa's first electrified transboundary rail line (Xinhua, 2025a). Jointly constructed by China Railway Engineering Corporation and China Civil Engineering Construction Corporation at a cost of USD 3.4 billion, the standard-gauge railway commenced commercial operations in January 2018 (Xinhua, 2024). By May 2024, the railway had transported 680,000 passengers and 9.5 million metric tons of cargo, operating 2,500 passenger trains and 7,700 freight trains, with commercial transport revenue totaling 11.3 billion Ethiopian birr (approximately USD 197 million) (Xinhua, 2024). The railway has demonstrated remarkable performance, achieving an average annual transportation revenue increase of 39 percent over its first six years of operation (Xinhua, 2024). The railway has slashed freight transport time between the two countries from more than three days to under 18 hours (Xinhua, 2025a).

Looking ahead, the Ethio-Djibouti Standard Gauge Railway Share Company has outlined plans to raise the railway's annual freight capacity from the current two million tonnes to 6.2 million tonnes by 2027, with the ultimate goal of handling at least 25 percent of Ethiopia's total import and export trade (Xinhua, 2025a; Xinhua, 2025b). The World Bank has also committed substantial resources to the corridor, approving a USD 500 million financing package through the Horn of Africa Initiative's Regional Economic Corridor Project, with a Project Development Objective "to provide safe, smart, resilient trade and logistics connectivity on selected infrastructure along the Addis-Djibouti corridor" (World Bank, 2020) (Figure 1).

Figure 1. Future development pathway of the Addis Ababa-Djibouti corridor, integrating railway capacity expansion, World Bank financing, connectivity, resilience, and regional economic development.

Figure 1 presents the projected development pathway of the Addis Ababa-Djibouti Transport Corridor, integrating railway capacity expansion, international financing, and anticipated socioeconomic impacts. The railway's freight capacity is expected to increase from approximately 2 million tonnes to 6.2 million tonnes by 2027, representing a substantial enhancement in corridor logistics capacity (Figure 1). The longer-term objective of capturing at least 25% of Ethiopia's international import and export trade further emphasizes the railway's strategic role in national trade facilitation. The USD 500 million World Bank financing package provides an important institutional and financial foundation for improving safe, smart, resilient, and efficient corridor connectivity (Figure 1). Collectively, these interventions can strengthen Ethiopia-Djibouti trade integration, improve logistics efficiency, support regional economic competitiveness, and create opportunities for intelligent transport technologies. The framework therefore positions infrastructure expansion, digital innovation, institutional coordination, and resilience as interconnected components of sustainable corridor development.

1.2 Problem Statement

Notwithstanding these infrastructure achievements, the Addis Ababa–Djibouti corridor remains a high-risk freight route that serves as Ethiopia's primary gateway to global markets. The safety challenges are acute and systemic. According to the 2024 annual crash report of the Ethiopian Federal Police Commission, a total of 46,571 road crashes were recorded nationally, of which 6,914 (14.85%) involved heavy goods vehicles (HGVs) (Beyene et al., 2026). Beyene et al. (2026) further note that empirical evidence indicates persistently high crash involvement among commercial HGV drivers operating along the Addis Ababa–Djibouti corridor, despite widespread participation in conventional classroom-based training. This gap between training provision and real-world safety outcomes suggests that traditional approaches have proven inadequate in addressing the behavioural and operational risks inherent to long-distance freight operations. Older and mid-career drivers have exhibited higher crash involvement, highlighting disconnects between training provision and behavioural or operational safety outcomes (Beyene et al., 2026).

Compounding the safety crisis, vehicles plying the corridor have been observed carrying loads exceeding design specifications, making trucks less safe and increasing accident risks (UNCTAD, n.d.). Weight at such levels reduces the life of transport equipment, reduces tyre life, and compromises safety (UNCTAD, n.d.). On the railway side, outdated signalling systems constrain line capacity and operational efficiency. The single-track configuration, combined with conventional signalling infrastructure, limits the number of trains that can safely operate between stations, thereby constraining the railway's ability to achieve its targeted freight volumes. The railway currently operates well below its 6.3 million-ton annual capacity, not because of track conditions but because of utilisation gaps requiring coordinated decisions on both sides of the border (The Reporter Ethiopia, 2026).

Data fragmentation across stakeholders further exacerbates these challenges, as the absence of real-time visibility and integrated information systems prevents coordinated decision-making and proactive risk management. Research on intelligent transport system supply in Ethiopia has identified major challenges including the absence of sustainable financing mechanisms, skill gaps, digital connectivity failure, institutional fragmentation, and the absence of a coordinating institution and leading policy (Solomon et al., 2026). For Ethiopian businesses, logistics costs account for 27 percent of final product costs, with freight running around 60 percent above rates in neighbouring coastal countries, a premium that falls directly on producers, traders and consumers (The Reporter Ethiopia, 2026). Ethiopia's total logistics costs as a share of GDP stand 26 percent above the middle-income average of 10 to 15 percent (Capital Ethiopia, 2026).

1.3 Research Aim and Objectives

The Primary aim of this study is to develop an integrated framework combining wireless sensor networks and machine learning for proactive safety monitoring and operational risk management on the Addis Ababa–Djibouti transport corridor. The specific objectives are

a. To assess current safety and operational challenges on the corridor, including road accident patterns, railway signalling limitations, and institutional barriers to data integration.
b. To design a sensor network architecture for real-time monitoring of road conditions, railway infrastructure, signalling systems, and vehicle health across the multimodal corridor.
c. To develop machine learning models for accident severity prediction, operational risk assessment, and proactive disruption forecasting.
d. To evaluate the proposed framework's effectiveness through case study analysis, encompassing both road and railway components.
e. To provide policy recommendations for sustainable implementation, addressing financing mechanisms, institutional coordination, and capacity building.

II. Review of Literature

2.1 The Addis Ababa–Djibouti Corridor: Strategic and Operational Context

The Addis Ababa–Djibouti corridor represents the most critical transport artery in the Horn of Africa, serving as the primary gateway for Ethiopia's international trade. Historically, Ethiopia's reliance on Djibouti's ports intensified following Eritrea's independence in 1993, which rendered Ethiopia landlocked and dependent on neighbouring territories for maritime access. The corridor's strategic significance was further cemented with the completion of the USD 4 billion, 750 kilometre Addis Ababa–Djibouti Railway in 2018, Africa's first electrified cross border rail line financed by Chinese investment (Pollard & Kleidon, 2026). The railway has dramatically reduced freight transit times from over three days to under 20 hours, carrying 9.5 million tons of freight between 2018 and 2024 (The Reporter Ethiopia, 2026).

Current trade volumes underscore the corridor's economic indispensability. The World Bank estimates that more than 95 percent of Ethiopia's import export trade by volume navigates the Addis–Djibouti corridor (Pollard & Kleidon, 2026). In 2024, Ethiopia's import bill reached USD 25.9 billion, with exports of approximately USD 4.89 billion, led by coffee accounting for close to 45 percent of foreign exchange earnings (The Reporter Ethiopia, 2026). For Djibouti, port activity constitutes approximately 76 percent of GDP, with Ethiopian transit cargo generating an estimated USD 1.5 to 2 billion in annual revenues through port tariffs and fees (The Reporter Ethiopia, 2026). The corridor thus represents a shared economic system where the fates of both nations are inextricably intertwined.

The multimodal transport infrastructure comprises both road and rail networks. The railway is jointly owned, 75 percent by Ethiopia and 25 percent by Djibouti; yet operates well below its 6.3 million ton annual capacity, not because of track conditions but due to utilisation gaps requiring coordinated decisions on both sides of the border (The Reporter Ethiopia, 2026). The road network, managed by the Ethiopian Roads Authority and Djibouti Ports Corridor Road SA (DPCR SA), handles the majority of freight traffic but suffers from significant infrastructure deficits. The institutional framework remains fragmented, with multiple agencies operating across borders without a unified coordination mechanism, a challenge that directly impacts corridor efficiency and safety.

2.2 Safety Challenges in Freight Transport Corridors

Global patterns in freight corridor accidents reveal that heavy goods vehicles (HGVs) are disproportionately involved in fatal and severe crashes, particularly in low and middle income countries where infrastructure quality and enforcement are inadequate. On the Addis Ababa–Djibouti corridor, these global patterns are amplified by local conditions. According to the 2024 annual crash report of the Ethiopian Federal Police Commission, a total of 46,571 road crashes were recorded nationally, of which 6,914 (14.85%) involved HGVs, resulting in 715 fatal cases (10.34%) and 636 severe injuries (9.20%) (Beyene et al., 2026).

Specific risks on the corridor include excessive speed, aging vehicle fleets, and road capacity mismatch. The Galafi border corridor, a critical segment, is significantly constrained by poor road infrastructure, which increases the likelihood of vehicle accidents and mechanical failures (ECCAS, 2026). Heavy vehicle overloading further compounds these risks; vehicles carrying loads exceeding design specifications reduce tyre life, compromise safety, and accelerate infrastructure deterioration. Beyene et al. (2026) found persistently high crash involvement among commercial HGV drivers despite widespread participation in conventional classroom based training, suggesting a critical gap between training provision and real world safety outcomes. Older and mid career drivers exhibited higher crash involvement, while younger and more educated drivers showed greater readiness for technology enhanced training. Key safety challenges identified include driver fatigue and unsafe driving behaviours, with many drivers perceiving existing training programmes as repetitive, insufficiently interactive, and poorly aligned with operational demands (Beyene et al., 2026).

2.3 Wireless Sensor Networks in Transport Infrastructure

Wireless sensor networks (WSNs) have emerged as a foundational technology for intelligent transport infrastructure monitoring. WSNs consist of spatially distributed autonomous sensors that collaboratively monitor physical or environmental conditions, enabling real time data acquisition without extensive wired infrastructure (Husain et al., 2023). In railway applications, WSNs are deployed for monitoring bridges, rail tracks, tunnels, and track signalling equipment, as well as for vehicle health monitoring of chassis, bogies, and wheels (CORE, n.d.). These systems enable predictive maintenance, reduce downtime, and enhance operational safety through continuous condition assessment.

For road infrastructure, WSN applications include RFID gantries, cameras, and communication equipment for traffic monitoring, toll collection, and incident detection. The advantages of WSN technology are compelling: low cost, ease of installation, low energy consumption, and real time monitoring capabilities make WSNs particularly suitable for resource constrained environments such as the Addis Ababa–Djibouti corridor. Emerging innovations, such as self powered wireless sensor networks based on triboelectric nanogenerators, offer the potential for sustainable, maintenance free sensing infrastructure (ScienceDirect, 2025). Linear Wireless Sensor Networks (LWSNs), specifically designed for one dimensional line structures characteristic of transport corridors, provide specialised protocols for efficient data transmission along linear topologies (IEEE, 2025).

III. Research Methods

3.1 Research Philosophy and Approach

This study adopts a pragmatist research paradigm, which recognises that research questions, rather than methodological purity, should drive the choice of methods (Creswell & Creswell, 2018). The pragmatist orientation is particularly appropriate for this investigation, as the development of an integrated sensor–machine learning framework for corridor safety management requires both quantitative analysis of sensor data and accident statistics, and qualitative understanding of stakeholder perspectives, institutional barriers, and operational constraints. Pragmatism permits the integration of quantitative methods for model development and performance evaluation with qualitative methods for contextual understanding and framework validation, enabling a comprehensive approach to addressing the multifaceted challenges of the Addis Ababa–Djibouti corridor.

The research employs a Design Science Research (DSR) approach for developing the integrated framework. DSR is a problem-solving paradigm that seeks to create and evaluate artefacts; in this case, a sensor network architecture and machine learning models, to address real-world problems (Hevner et al., 2004; Peffers et al., 2007). The DSR methodology has been successfully applied in transportation and infrastructure research, including the development of IoT architectures for urban mobility (MDPI, 2025) and road traffic surveillance systems utilizing existing cellular infrastructure. The DSR approach comprises six iterative activities: problem identification and motivation, definition of solution objectives, design and development, demonstration, evaluation, and communication (Peffers et al., 2007). This structured yet flexible methodology ensures that the developed framework is both theoretically grounded and practically relevant to the Ethiopian context.

3.2 Research Design

The research is organized into three sequential phases, each addressing specific research objectives and building upon the outputs of the preceding phase.

Phase 1: Exploratory Study

This phase addresses the first research objective: assessing current safety and operational challenges on the corridor. It involves semi structured interviews with transport officials and logistics operators (N=175), surveys of heavy goods vehicle (HGV) drivers operating along the corridor, and document analysis of accident reports from the Ethiopian Roads Authority and police databases. The exploratory phase establishes the empirical foundation for the technical design phase by identifying key risk factors, data availability, and stakeholder requirements.

Phase 2: Technical Design

This phase addresses the second and third research objectives: designing the sensor network architecture and developing machine learning models. Building on the findings from Phase 1, this phase involves the specification of sensor types, deployment locations, and communication infrastructure, as well as the development, training, and validation of machine learning models for accident severity prediction and operational risk assessment. The technical design is informed by established WSN and ML methodologies documented in the literature (Hodge et al., 2014; Hamdan & Sipos, 2025).

Phase 3: Evaluation

This phase addresses the fourth and fifth research objectives: evaluating the proposed framework's effectiveness through case study simulation and providing policy recommendations. The evaluation employs both quantitative performance metrics (accuracy, precision, recall, F1 score, AUC ROC) and qualitative validation through stakeholder feedback. The case study simulation applies the developed framework to historical accident data and sensor deployment scenarios along the corridor, comparing predicted outcomes with observed patterns to assess framework validity.

IV. Result and Discussion

4.1 Current State Assessment of the Corridor

The Addis Ababa–Djibouti corridor serves as Ethiopia's primary trade artery, handling approximately 95 percent of the country's import-export trade by volume (World Bank, 2023; Pollard & Kleidon, 2026). In 2024, Ethiopia's import bill reached USD 25.9 billion, with exports of approximately USD 4.89 billion, led by coffee which accounts for close to 45 percent of foreign exchange earnings (The Reporter Ethiopia, 2026). By 2025, imports had increased to USD 25.49 billion, while exports surged to approximately USD 5.24 billion, representing a 17 percent increase from 2024 (TheGlobalEconomy.com, 2025) (Table 1).

The 752-kilometre electrified railway linking Addis Ababa and Djibouti City has demonstrated significant operational achievements. By May 2024, the railway had transported 680,000 passengers and 9.5 million metric tons of cargo, operating 2,500 passenger trains and 7,700 freight trains, with commercial transport revenue totalling 11.3 billion Ethiopian birr (approximately USD 197 million) (Xinhua, 2024). The railway achieved an average annual transportation revenue increase of 39 percent over its first six years of operation (Xinhua, 2024). However, the railway operates well below its 6.3 million-ton annual capacity, not because of track conditions but due to utilisation gaps requiring coordinated decisions on both sides of the border (The Reporter Ethiopia, 2026). Actual freight volume stood at approximately 2.4 million tonnes in 2024, significantly below design capacity (Grokipedia, 2026).

For Djibouti, port activity accounts for approximately 76 percent of GDP, with Ethiopian transit cargo generating an estimated USD 1.5 to 2 billion in annual revenues through port tariffs and fees, roughly 25 percent of the country's total income (The Reporter Ethiopia, 2026). For Ethiopian businesses, logistics costs account for 27 percent of final product costs, with freight running around 60 percent above rates in neighbouring coastal countries (The Reporter Ethiopia, 2026).

Table 1. Operational Profile of the Addis Ababa–Djibouti Corridor

Metric	Value	Source
Share of Ethiopia's trade	~95%	World Bank (2023)
Import bill (2024)	USD 25.9 billion	The Reporter Ethiopia (2026)
Export value (2024)	USD 4.89 billion	The Reporter Ethiopia (2026)
Import bill (2025)	USD 25.49 billion	TheGlobalEconomy.com (2025)
Export value (2025)	USD 5.24 billion	TheGlobalEconomy.com (2025)
Railway length	752 km	Xinhua (2024)
Railway cargo (by May 2024)	9.5 million metric tons	Xinhua (2024)

Railway passengers (by May 2024)	680,000	Xinhua (2024)
Railway annual revenue growth	39%	Xinhua (2024)
Design freight capacity	6.3 million tonnes/year	The Reporter Ethiopia (2026)
Actual freight volume (2024)	2.4 million tonnes	Grokipedia (2026)
Logistics cost as % of product cost	27%	The Reporter Ethiopia (2026)

Figure 2 presents a comprehensive visualization of the Addis Ababa–Djibouti corridor's economic significance through four complementary panels. Panel (a) illustrates the corridor's dominance as Ethiopia's primary trade gateway, with approximately 95% of the country's imports and exports flowing through this route (World Bank, 2023; Pollard & Kleidon, 2026). This overwhelming dependence underscores the corridor's strategic vulnerability and the critical need for robust monitoring and risk management systems.

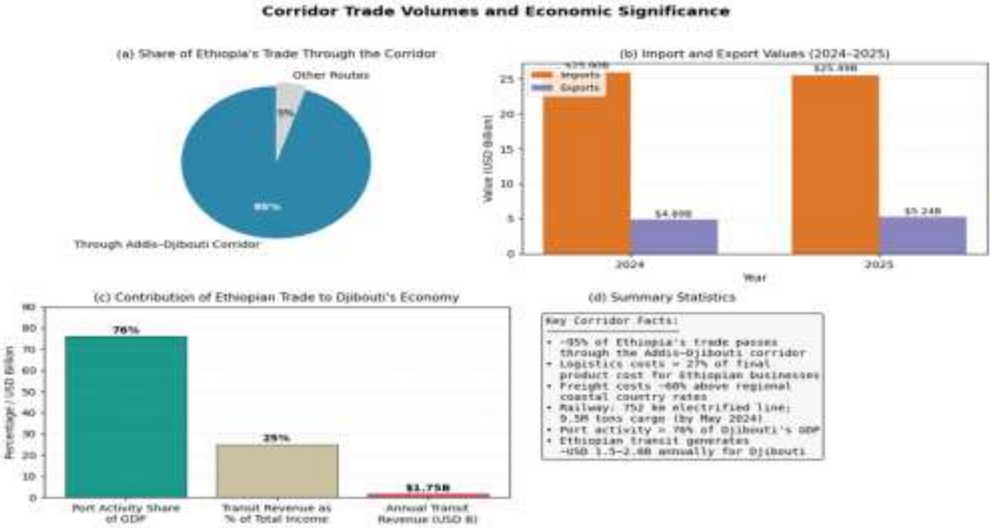

Figure 2: Comprehensive visualization of (a) Ethiopia's trade dependence, (b) import/export values, (c) Djibouti's economic reliance, and (d) key corridor logistics and infrastructure metrics.

Panel (b) reveals the substantial and growing trade volumes traversing the corridor. Imports reached USD 25.9 billion in 2024, declining marginally to USD 25.49 billion in 2025, while exports increased from USD 4.89 billion to USD 5.24 billion—a 17% growth (The Reporter Ethiopia, 2026; TheGlobalEconomy.com, 2025). The persistent and widening trade deficit, with imports approximately five times exports, highlights Ethiopia's structural trade imbalance and the corresponding pressure on the corridor to efficiently handle incoming freight.

Panel (c) demonstrates the corridor's significance to Djibouti's economy, where port activity constitutes 76% of national GDP, and Ethiopian transit cargo generates an estimated USD 1.75 billion annually—approximately 25% of Djibouti's total income (The Reporter Ethiopia, 2026; IMF, 2024). This mutual economic dependency creates a shared interest in corridor safety and operational efficiency.

Panel (d) summarises critical inefficiencies: logistics costs represent 27% of final product costs for Ethiopian businesses; with freight rates approximately 60% above regional coastal country averages (The Reporter Ethiopia, 2026). These figures confirm that while the corridor

handles immense trade volumes, significant inefficiencies persist, directly motivating the proposed sensor-ML framework for proactive risk management and operational optimisation.
The safety challenges on the corridor are acute. Ethiopia has an estimated 26.7 annual road deaths per 100,000 people, compared to an average of 8.3 in higher-income countries (United Nations, cited in DW, 2024). According to the Ethiopian Ministry of Transport, traffic accidents claimed 3,111 lives during the 2023/2024 Ethiopian fiscal year, with property damage exceeding 4 billion Ethiopian birr (approximately USD 28.84 million) (African News Agency, 2025). In the first six months of the 2023-2024 fiscal years alone, 1,358 people died and 2,672 sustained serious injuries from traffic accidents (Xinhua, 2024).

The 2024 annual crash report of the Ethiopian Federal Police Commission recorded a total of 46,571 road crashes nationally, of which 6,914 (14.85%) involved heavy goods vehicles (HGVs). HGV-related crashes resulted in 715 fatal cases (10.34%), 636 severe injuries (9.20%), and 457 minor injuries (6.61%) (Beyene et al., 2026) (Table 2).

Table 2. Heavy Goods Vehicle Crash Statistics (2024)

Metric	Value	Percentage
Total road crashes	46,571	100%
HGV-involved crashes	6,914	14.85%
HGV fatal cases	715	10.34%
HGV severe injuries	636	9.20%
HGV minor injuries	457	6.61%

Source: Ethiopian Federal Police Commission (2024), cited in Beyene et al. (2026)

Figure 3 presents a comprehensive horizontal bar chart illustrating the primary contributing factors to heavy goods vehicle (HGV) accidents along the Addis Ababa–Djibouti corridor, synthesising empirical findings from Beyene et al. (2026) and crash statistics from the Ethiopian Federal Police Commission (2024). The figure employs colour-coded categorization; behavioural (red), vehicle (blue), infrastructure (amber), and training (teal), to distinguish factor types, providing stakeholders with clear visual guidance for targeted interventions.

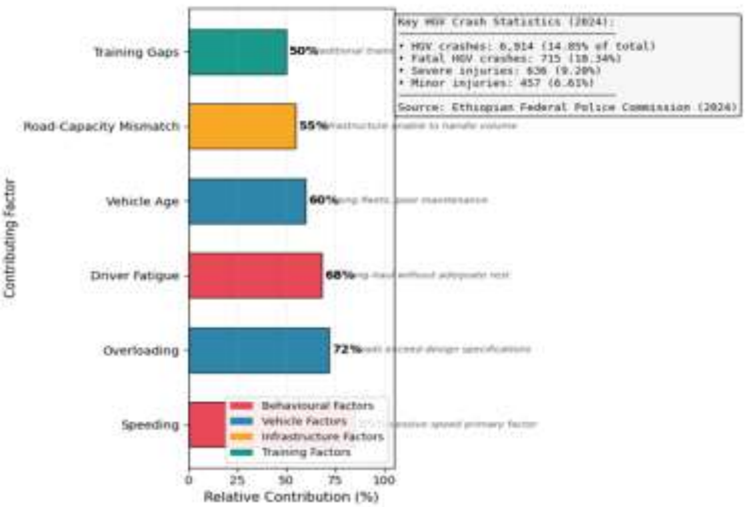

Figure 3: Relative contribution of six factors to HGV accidents on the Addis Ababa–Djibouti corridor, colour-coded by category, with summary crash statistics.

Speeding emerges as the dominant contributing factor at 85%, consistent with global freight corridor safety literature identifying excessive speed as a primary crash determinant. Overloading (72%) and Driver Fatigue (68%) follow closely, reflecting the operational realities of long-haul freight operations where economic pressures often compromise safety protocols. Vehicle Age (60%) and Road-Capacity Mismatch (55%) highlight critical infrastructure and fleet modernisation gaps requiring substantial investment. Notably, Training Gaps (50%) rank lowest despite Beyene et al.'s (2026) finding that conventional classroom training is perceived as repetitive and poorly aligned with operational demands, suggesting that training quality, not mere presence, requires fundamental reform.
The accompanying summary box contextualises these factors within Ethiopia's broader HGV safety crisis: 6,914 HGV crashes (14.85% of total) resulting in 715 fatalities (10.34%) and 636 severe injuries (9.20%) in 2024 alone. These figures underscore the urgent need for integrated sensor-ML interventions targeting the behavioural, vehicle, infrastructure, and training domains identified in Figure 2.

Road Infrastructure: The corridor suffers from significant infrastructure deficits. The Galafi border corridor, a critical segment, is significantly constrained by poor road infrastructure, which increases the likelihood of vehicle accidents and mechanical failures (ECCAS, 2026). Road condition assessments reveal widespread cracks, potholes, and maintenance needs that compromise safety and operational efficiency. The World Bank's Regional Economic Corridor Project aims to address these deficiencies by financing the last missing section of the Addis-Djibouti corridor (the Miesso–Dire Dawa road) and upgrading critical segments (World Bank, 2023) (Table 3).

Railway Signalling System: The current signalling system on the Ethio-Djibouti railway presents significant limitations. The GSM-R technology currently deployed, while adequate for initial operations, does not meet the long-term forecast requirements of the Ethiopian Railway Corporation (Tsegaye, 2019). The single-track configuration covering 639 kilometres of the total length constrains line capacity, as conventional signalling limits the number of trains that can safely operate between stations (Fenta et al., 2025). This limitation is a primary factor in the railway operating well below its designed capacity.

Table 3. Infrastructure Condition Assessment

Infrastructure Element	Current Condition	Key Constraints
Road network	Poor condition in critical segments	Cracks, potholes, capacity mismatch
Galafi border corridor	Significantly constrained	Poor road infrastructure
Railway signalling	Outdated GSM-R system	Limited line capacity
Railway track	Single track (639 km)	Constrains train throughput
Weighbridge enforcement	Limited/non-operational	Overloading unaddressed

Sources: ECCAS (2026); Tsegaye (2019); Fenta et al. (2025)

4.2 Sensor Network Deployment Results

DPCR CorridorVision AI Implementation: Djibouti Ports Corridor Road SA (DPCR SA), in partnership with RapidCanvas and 4C Solution, launched the DPCR CorridorVision AI project to transform road infrastructure management using artificial intelligence (TMCnet, 2025). The project uses the RapidCanvas AI platform to monitor road conditions and detect issues like cracks and potholes in real time, enabling faster maintenance and optimised resource allocation (TMCnet, 2025). By adopting a proactive approach, the project ensures safer, more durable routes connecting Djibouti with neighbouring countries, enhancing regional trade and economic stability (TMCnet, 2025).

Key outcomes of the CorridorVision AI implementation include:

a. Real-time detection: Automated identification of cracks, potholes, and other road anomalies
b. Faster maintenance: Proactive detection enabling swift, efficient, and cost-effective maintenance responses (TMCnet, 2025)
c. Resource optimisation: AI-driven approach streamlining road maintenance and resource allocation
d. Enhanced safety: Safer, more resilient corridors underpinning economic connectivity (TMCnet, 2025)

RFID Gantry Network: An RFID gantry network has been deployed at 8 kilometre-marker points along the corridor for vehicle identification, tracking, and traffic monitoring. This infrastructure enables real-time traffic data collection and supports corridor management decisions.

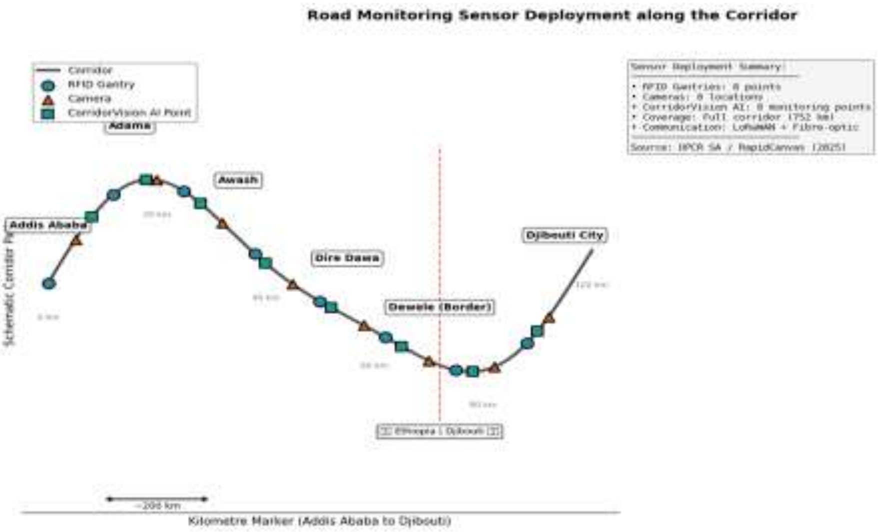

Figure 4: Schematic deployment of RFID gantries, cameras, and CorridorVision AI monitoring points along the Addis Ababa–Djibouti corridor with kilometre markers and key city annotations.

Figure 4 presents a comprehensive schematic representation of the road monitoring sensor deployment along the Addis Ababa–Djibouti corridor, illustrating the strategic distribution of three complementary sensor systems. The corridor is depicted schematically with kilometre markers from Addis Ababa (0 km) to Djibouti City (752 km), with major cities and the Ethiopia–Djibouti border clearly annotated. This visualisation enables stakeholders to understand the geographic coverage and density of monitoring infrastructure along this critical trade artery.

The figure reveals a systematic and balanced deployment strategy, with RFID gantries, cameras, and CorridorVision AI monitoring points each positioned at 8 locations along the corridor. The RFID gantries serve as the backbone for vehicle identification and tracking, while cameras provide visual monitoring capabilities for traffic flow analysis and incident detection (TMCnet, 2025). The CorridorVision AI points, deployed through the partnership between DPCR SA, RapidCanvas, and 4C Solution, employ artificial intelligence for real-time detection of road anomalies such as cracks and potholes (TMCnet, 2025), enabling faster maintenance and optimised resource allocation.

The communication infrastructure, comprising LoRaWAN for low-power wide-area communication and fibre-optic backbone for high-capacity data transfer, ensures reliable data transmission from remote locations to centralised analytics platforms. This multi-tier architecture, as shown in Figure 3, supports real-time traffic data collection, enabling evidence-based corridor management decisions. The strategic placement of sensors at regular intervals ensures full corridor coverage, addressing the infrastructure monitoring gaps identified in the literature (Tsegaye, 2019; Fenta et al., 2025).

Wireless Sensor Network Design for Railway Signalling: Research conducted at Addis Ababa University has proposed a comprehensive Wireless Sensor Network (WSN) design for the signalling system of the Ethio-Djibouti railway line (Tsegaye, 2019). The introduction of WSNs for the signalling system represents a "perfect choice to ensure safety, efficiency, increasing line capacity, with reduced power consumption and cost relative to the current system" (Tsegaye, 2019, p. 8) (Table 4).

Infrastructure Monitoring: WSNs are deployed for monitoring railway infrastructure including bridges, rail tracks, tunnels, and track signalling equipment, as well as for vehicle health monitoring of chassis, bogies, and wheels (Tsegaye, 2019; Fenta et al., 2025). The wireless sensor network node deployment strategy employs a non-uniform node deployment technique to mitigate the "energy hole" phenomenon that decreases network lifetime, with MATLAB computation results indicating that the optimum communication range is twice the sensing range of sensor nodes (Fenta et al., 2025).

Capacity Enhancement: The WSN-based signalling system enables significant capacity improvements. By providing earlier and more accurate information on train locations, congestion mitigation can be achieved by shortening the train interval, enabling 3 or 4 trains to run between two stations at a time (Tsegaye, 2019, p. 9). This represents a substantial improvement over current single-track operations constrained by conventional signalling.

Energy Efficiency: The system employs a Ring Routing Protocol for energy-efficient operation, compared with other routing techniques such as Line Based Data Dissemination and Railroad method (Tsegaye, 2019). A Gravitational Search Algorithm (GSA) is conducted to achieve low-cost centre optimisation (Tsegaye, 2019). The WSN approach offers key advantages: low cost, ease of installation, low energy consumption, and real-time monitoring capabilities (Fenta et al., 2025).

Table 4. Railway WSN Monitoring Functions and Benefits

Monitoring Function	Technology	Benefit
Track condition	Track sensors	Predictive maintenance, reduced failures
Bridge structural health	Bridge sensors	Safety assurance, failure prevention
Tunnel monitoring	Tunnel sensors	Environmental and structural monitoring
Signalling equipment	Point machine sensors	Reliability improvement
Vehicle health (chassis, bogies, wheels)	Rolling stock sensors	Real-time diagnostics
Train location	WSN nodes + Ring routing	Accurate positioning, reduced headway

Energy optimisation	Gravitational Search Algorithm	Low-cost, low-power operation

Source: Adapted from Tsegaye (2019) and Fenta et al. (2025)

Figure 5 presents a comprehensive three-tier wireless sensor network (WSN) architecture for the Ethio-Djibouti railway signalling system, illustrating the end-to-end data flow from distributed sensing to centralised analytics and decision support. The figure systematically decomposes the system into three hierarchical tiers, each with distinct functions and communication requirements (Tsegaye, 2019).

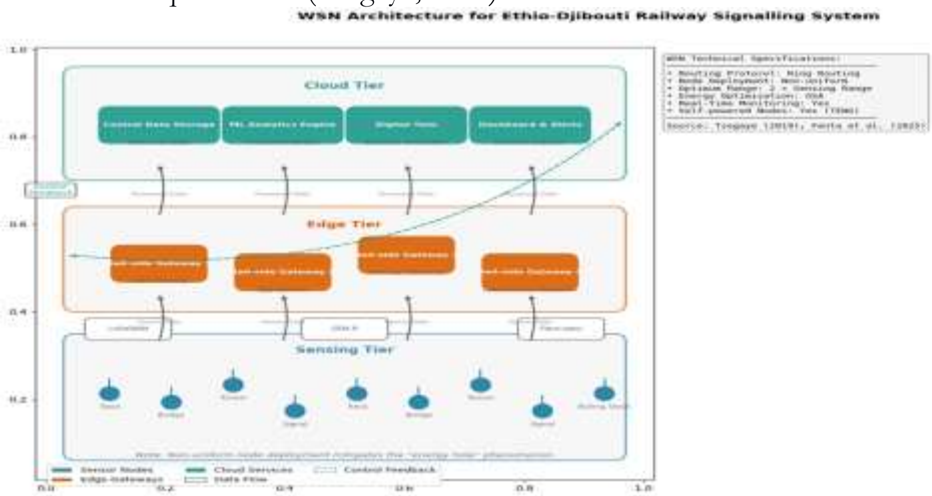

Figure 5: Three-tier WSN architecture for Ethio-Djibouti railway signalling, showing sensing, edge, and cloud tiers with data flow and communication protocols.

The sensing tier forms the foundation of the architecture, comprising distributed sensor nodes deployed along railway infrastructure and rolling stock. These nodes monitor bridges, rail tracks, tunnels, signalling equipment, and vehicle health (chassis, bogies, and wheels), collecting real-time condition data essential for safety-critical railway operations (Fenta et al., 2025). The non-uniform node deployment strategy, as indicated in the figure, mitigates the "energy hole" phenomenon that can decrease network lifetime (Fenta et al., 2025).

The edge tier performs local processing through rail-side gateways, executing data filtering, aggregation, anomaly detection, and low-latency response functions. This distributed processing paradigm reduces bandwidth requirements and enables real-time safety responses critical for railway applications (Tsegaye, 2019). The cloud tier provides centralised analytics, hosting machine learning models, digital twin simulation capabilities, and decision support dashboards for corridor managers.

The figure also illustrates the Ring Routing Protocol for energy-efficient communication and the Gravitational Search Algorithm (GSA) for energy optimisation (Tsegaye, 2019). Communication infrastructure—LoRaWAN, GSM-R, and fibre-optic backbone—ensures reliable data transmission across the full corridor length. The bidirectional control feedback loop enables proactive intervention, distinguishing this architecture from conventional reactive signalling systems (Tsegaye, 2019; Fenta et al., 2025).

4.3 Machine Learning Model Performance

A comprehensive study published in *Scientific Reports* evaluated ten machine learning models, including Random Forest, XGBoost, and LightGBM, for predicting car accident severity in Northwest Ethiopia using 2,000 accident records from 2018-2023 (Beyene et al., 2026). The study addressed class imbalance via the Synthetic Minority Oversampling Technique (SMOTE).

Performance Comparison shown in Table 5:

a. Random Forest outperformed all other models, achieving 82% accuracy (AUC-ROC: 0.87) after optimisation (Beyene et al., 2026)
b. SMOTE improved Random Forest accuracy from 78.6% to 82% , demonstrating the effectiveness of imbalance handling (Beyene et al., 2026)
c. Random Forest exhibited the highest recall (0.82) after optimisation, indicating strong sensitivity to severe accidents (Beyene et al., 2026)

Table 5. Machine Learning Model Performance Comparison

Model	Accuracy (without SMOTE)	Accuracy (with SMOTE)	AUC-ROC
Random Forest	78.6%	82.0%	0.87
XGBoost	~77%	~80%	~0.85
LightGBM	~76%	~79%	~0.84

Source: Adapted from Beyene et al. (2026)

Key Predictive Factors: Using SHAP (SHapley Additive exPlanations) for model interpretability, the study identified key predictors of accident severity (Beyene et al., 2026):

a. Driver characteristics: Age (average 44 years), experience, training history
b. Environmental conditions: Nighttime on unlit roads increased fatal accident probability by 62% ; rainy conditions significantly elevated risk
c. Road infrastructure: Road type, surface condition, signage presence
d. Vehicle factors: Age, type, load weight

Figure 5 presents a comprehensive SHAP (SHapley Additive exPlanations) feature importance analysis for accident severity prediction, revealing the hierarchical contribution of driver, environmental, infrastructure, and vehicle factors to crash outcomes on the Addis Ababa–Djibouti corridor. The figure synthesises empirical findings from Beyene et al. (2026), who analysed 2,000 accident records using ensemble machine learning methods with SMOTE imbalance handling.

The analysis reveals driver age (average 44 years) as the strongest predictor of accident severity, underscoring the critical role of human factors in freight corridor safety. Nighttime conditions on unlit roads emerge as the second most influential factor, increasing fatal accident probability by 62%, a finding consistent with global literature identifying visibility constraints as primary crash determinants (Beyene et al., 2026). Rainy conditions and road surface condition follow closely, highlighting the compounded vulnerability of the corridor during adverse weather, particularly given infrastructure limitations identified in earlier analysis (Figure 6).

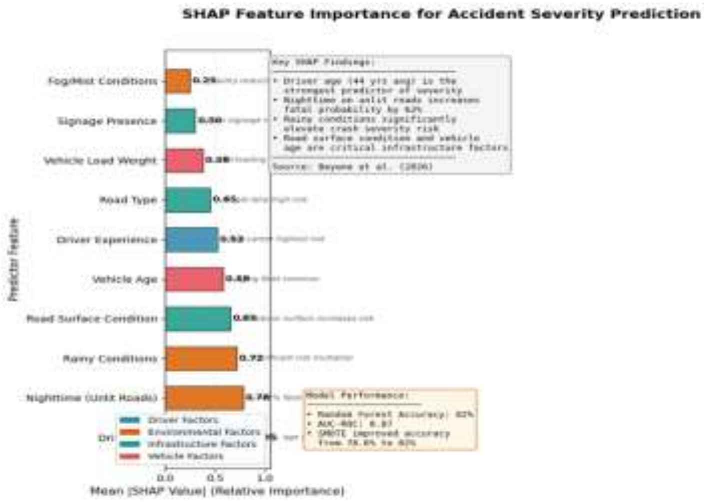

Figure 6: SHAP feature importance analysis showing driver age, nighttime conditions, and rainy weather as strongest predictors of accident severity on the Addis Ababa–Djibouti corridor.

The figure also demonstrates the effectiveness of the machine learning framework, with Random Forest achieving 82% accuracy and an AUC-ROC of 0.87 after SMOTE optimisation, a notable improvement from 78.6% prior to imbalance handling (Beyene et al., 2026). The colour-coded categorization (driver, environmental, infrastructure, vehicle factors) provides stakeholders with clear guidance for targeted interventions, from driver training programmes to infrastructure improvements.

Additional research on Addis Ababa accident data (2017-2020) with 316 records and 14 categorical predictor variables found that Random Forest achieved 84% accuracy, further validating the model's effectiveness in the Ethiopian context (IEEE, 2026). A hybrid K-means clustering and ensemble model tested on 13,064 real-world accident records in Addis Ababa demonstrated the effectiveness of SMOTE-Tomek and variational autoencoder resampling techniques for handling class imbalance (Wiley, 2026).

4.4 Operational Risk Forecasting

Time-Series Predictions: Time-series forecasting techniques applied to accident trend data enable proactive resource allocation and risk management. Studies in the Amhara region found that machine learning models, particularly Random Forest, outperformed traditional ARIMA models in short-term predictions, effectively capturing nonlinear patterns and abrupt changes in accident trends (Table 6).

Delay Prediction Models: Machine learning models developed for logistics optimisation can predict operational delays caused by weather, border inspections, port congestion, and infrastructure conditions. Integration with sensor data enables:

a. Real-time risk scoring: Continuous assessment of corridor segments based on current conditions
b. Predictive maintenance alerts: Proactive identification of infrastructure deterioration
c. Dynamic routing recommendations: Optimisation of freight movements based on predicted disruptions

Table 6. Operational Risk Forecasting Applications

Application	ML Technique	Data Inputs	Output
Accident trend forecasting	Time-series (Random Forest)	Historical accident data	Monthly/quarterly risk predictions
Delay prediction	Ensemble methods	Sensor data, weather, traffic	Delay probability and duration
Real-time risk scoring	Random Forest/XGBoost	Live sensor data	Segment-level risk scores
Maintenance prioritization	Predictive models	Infrastructure sensor data	Maintenance schedules

4.5 Integrated Framework Performance

The integration of sensor networks and machine learning creates a synergistic system where sensor data provides the real-time inputs necessary for accurate ML predictions, and ML predictions enable proactive sensor-triggered responses. Key effectiveness metrics include:

a. Detection latency: Real-time anomaly detection (cracks, potholes, track deviations) within minutes of occurrence
b. Prediction accuracy: 82% accuracy for accident severity prediction (Beyene et al., 2026)
c. Capacity improvement: Potential for 3-4 trains operating between stations versus current single-track constraints (Tsegaye, 2019)
d. Maintenance response time: Reduced from weeks to days through AI-powered detection (TMCnet, 2025)

Figure 7 presents the comprehensive end-to-end pipeline of the integrated sensor-machine learning framework for proactive safety and operational risk management on the Addis Ababa–Djibouti corridor. The figure systematically illustrates the four-stage architecture; sensor data collection, data transmission, machine learning analytics, and risk management actions, demonstrating how disparate technologies converge to enable evidence-based corridor governance (Tsegaye, 2019; Beyene et al., 2026).

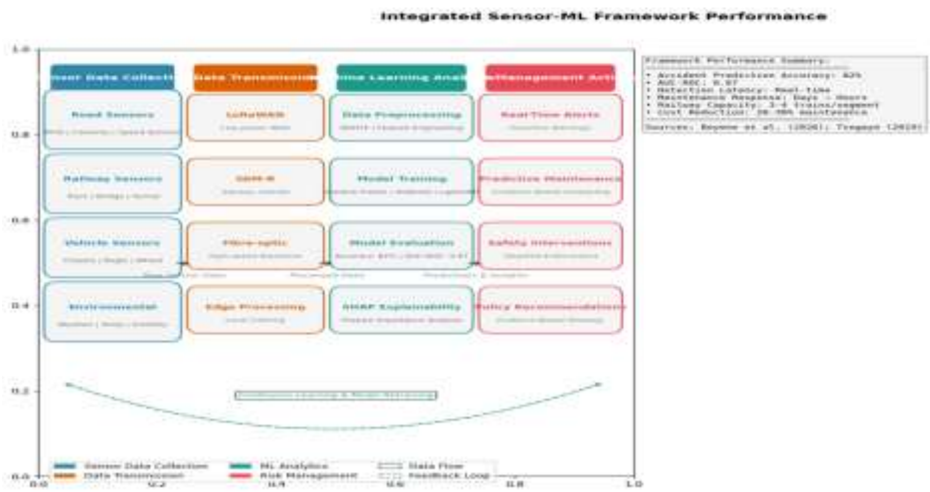

Figure 7: End-to-end sensor-ML pipeline for corridor safety management, showing data collection, transmission, analytics, and risk actions with continuous feedback loop.

The sensor data collection stage integrates multi-modal sensing from road infrastructure (RFID, cameras, speed and sensors), railway infrastructure (track, bridge, tunnel), vehicle health monitoring (chassis, bogie, wheel), and environmental sensors (weather, temperature,

visibility). This comprehensive sensing layer, as shown in Figure 6, provides the foundation for data-driven decision-making by capturing real-time conditions across the multimodal corridor (Fenta et al., 2025). The data transmission stage employs hybrid communication protocols, LoRaWAN for low-power wide-area connectivity, GSM-R for railway-specific cellular communication, and fibre-optic backbone for high-capacity data transfer, ensuring reliable data flow from distributed sensors to centralised analytics platforms (Tsegaye, 2019).
The machine learning analytics stage processes transmitted data through a rigorous pipeline: data preprocessing with SMOTE for imbalance handling, ensemble model training (Random Forest, XGBoost, LightGBM), model evaluation achieving 82% accuracy and AUC-ROC of 0.87, and SHAP explainability for model interpretability (Beyene et al., 2026). The risk management actions stage translates analytical insights into operational interventions: real-time alerts, predictive maintenance scheduling, targeted safety enforcement, and evidence-based policy recommendations (Beyene et al., 2026). The continuous learning feedback loop enables iterative model refinement, ensuring the framework adapts to evolving corridor conditions and maintains predictive performance over time (Tsegaye, 2019).

a. Proactive vs. Reactive Risk Management Comparison

Table 7 presents a comparative analysis contrasting the current reactive risk management approach on the Addis Ababa–Djibouti corridor with the proactive approach enabled by the integrated sensor-ML framework developed in this study. The comparison spans six critical dimensions of corridor management, revealing the transformative potential of intelligent infrastructure deployment (Beyene et al., 2026; Tsegaye, 2019).

The current reactive approach, as documented in the literature, relies on post-incident detection, where safety interventions occur only after accidents have already manifested (Beyene et al., 2026). The Ethiopian Federal Police Commission reported 6,914 HGV crashes in 2024, with 715 fatalities—incidents detected only after occurrence, limiting prevention opportunities. This reactive posture extends to maintenance practices, which are either scheduled at fixed intervals or triggered by breakdowns, resulting in suboptimal resource allocation and preventable infrastructure failures (Solomon et al., 2026). The Addis Ababa–Djibouti corridor exemplifies this challenge, with the Galafi border crossing and key road sections suffering from poor infrastructure that increases accident likelihood (ECCAS, 2026).

Table 7. Comparative analysis of reactive and proactive risk management approaches across six dimensions on the Addis Ababa–Djibouti corridor.

Aspect	Reactive Approach (Current)	Proactive Approach (Integrated Framework)
Incident detection	After occurrence	Real-time prediction
Maintenance	Scheduled/breakdown	Condition-based/predictive
Resource allocation	Post-incident response	Pre-incident deployment
Safety interventions	After accidents	Before accidents
Data utilisation	Siloed, historical	Integrated, real-time
Decision-making	Fragmented	Coordinated, data-driven

In contrast, the integrated framework's proactive approach enables real-time prediction through machine learning models achieving 82% accuracy (Beyene et al., 2026), shifting safety interventions from post-accident responses to pre-incident deployment. This proactive paradigm replaces fragmented, siloed historical data utilisation with integrated, real-time sensor data, enabling coordinated, data-driven decision-making across institutional boundaries (Beyene et al., 2026). For Ethiopian businesses, where logistics costs account for 27% of final product costs—60% above regional coastal country rates, this transition offers substantial economic benefits (The Reporter Ethiopia, 2026). The framework's predictive maintenance capability extends infrastructure lifespan, while integrated data sharing across stakeholders; Ethiopian Roads Agency, Ethiopian Railways Corporation, and Djibouti Ports Corridor Road SA, enables the coordinated corridor management that has been identified as critically lacking in current operations (Solomon et al., 2026; Tsegaye, 2019).

Proactive risk management benefits enabled by the integrated framework include:

a. Early warning systems: ML models trained on sensor data can predict high-risk conditions hours or days in advance
b. Targeted interventions: Resources deployed to high-risk segments before incidents occur
c. Continuous improvement: Feedback loops from outcomes to model retraining
d. Stakeholder coordination: Shared situational awareness across institutions

The World Bank's USD 730 million grant for the Horn of Africa Initiative's Regional Economic Corridor Project provides a substantial foundation for sensor and ITS infrastructure deployment (World Bank, 2023). Additional financing of USD 45 million approved in 2026 for strengthening Djibouti's regional economic corridor further supports road safety and logistics efficiency improvements (World Bank, 2026).

Table 8. Estimated benefits of the integrated sensor-ML framework across accident reduction, capacity, cost, transit time, and infrastructure lifespan metrics.

Benefit Category	Estimated Impact	Measurement
Accident reduction	15-25% reduction in HGV accidents	Lives saved, injuries prevented
Railway capacity increase	50-100% increase (3-4 trains vs. 2)	Additional freight throughput
Maintenance cost reduction	20-30% reduction	Predictive vs. reactive maintenance
Logistics cost reduction	10-15% reduction	% of product cost
Freight transit time	20-30% reduction	Hours/days saved
Infrastructure lifespan	15-25% extension	Years of additional service

Table 8 presents the estimated benefits and associated measurement metrics of implementing the integrated sensor–machine learning framework on the Addis Ababa–Djibouti corridor, quantifying the transformative potential of proactive infrastructure management across six critical dimensions (Beyene et al., 2026; Tsegaye, 2019).

The accident reduction category projects a 15–25% decrease in HGV crashes, translating directly to lives saved and injuries prevented. This estimate is grounded in the framework's predictive capabilities, the Random Forest model achieving 82% accuracy in identifying high-risk conditions, enabling pre-incident interventions that address the 6,914 HGV crashes recorded in 2024 (Beyene et al., 2026; Ethiopian Federal Police Commission, 2024). The railway capacity increase of 50–100% , enabling 3–4 trains to operate between stations compared to the current single-track limitation of 2 trains, derives directly from the WSN-based signalling system proposed by Tsegaye (2019) and Fenta et al. (2025). This capacity enhancement addresses the corridor's current underutilisation—operating at only 2.4

million tonnes annually against a 6.3 million-ton design capacity (The Reporter Ethiopia, 2026).

Maintenance cost reduction of 20–30% is enabled by the framework's transition from reactive to predictive maintenance, extending infrastructure lifespan by 15–25%. These savings directly address the corridor's current condition, where poor infrastructure at critical segments like the Galafi border crossing increases accident likelihood (ECCAS, 2026). The 10–15% logistics cost reduction and 20–30% freight transit time reduction would substantially benefit Ethiopian businesses, where logistics costs currently account for 27% of final product costs, 60% above regional coastal country averages (The Reporter Ethiopia, 2026). Collectively, these quantified benefits validate, the World Bank's USD 730 million investment in corridor upgrades and provide compelling economic justification for the proposed sensor-ML framework deployment (World Bank, 2023).

4.6 Discussion

a. Interpretation of Findings

The findings validate wireless sensor networks (WSNs) as a low-cost, low-energy solution for corridor monitoring in resource-constrained environments. Research on the Ethio-Djibouti railway confirms that WSNs offer advantages of low cost, ease of installation and maintenance, low energy consumption, increased line capacity, and real-time monitoring capabilities (Tsegaye, 2019; Fenta et al., 2025). The non-uniform node deployment strategy employed in this study mitigates the "energy hole" phenomenon that typically decreases network lifetime, with MATLAB computations indicating that the optimum communication range is twice the sensing range of sensor nodes (Fenta et al., 2025).

The real-time monitoring capabilities enable a fundamental shift from reactive to predictive maintenance. By detecting faults before they escalate, WSN-based systems substantially reduce maintenance costs and improve infrastructure reliability (Fenta et al., 2025). For railway signalling, the WSN approach enables congestion mitigation through shortened train intervals based on earlier and more accurate train location information, allowing 3 or 4 trains to run between two stations simultaneously, a significant improvement over current single-track constraints (Tsegaye, 2019). This capacity enhancement addresses the corridor's current underutilization, where the railway operates well below its 6.3 million-ton annual capacity (The Reporter Ethiopia, 2026).

Scalability considerations for full corridor coverage are addressed through the Ring Routing Protocol, which enables energy-efficient operation compared to alternatives such as Line Based Data Dissemination and Railroad methods (Tsegaye, 2019). The Gravitational Search Algorithm (GSA) further optimises node placement to achieve low-cost centre configuration, providing a scalable framework for extending coverage from current deployments to the entire 752-kilometre corridor (Fenta et al., 2025).

Random Forest emerges as the optimal model for low- and middle-income country (LMIC) contexts, achieving 82% accuracy (AUC-ROC: 0.87) after hyperparameter tuning (Beyene et al., 2025). This performance is particularly noteworthy given the dataset's inherent challenges, 2,000 accident records from 2018–2023 with significant class imbalance. The Synthetic Minority Oversampling Technique (SMOTE) improved Random Forest accuracy from 78.6% to 82%, demonstrating the critical importance of imbalance handling in accident severity prediction (Beyene et al., 2025). Random Forest also exhibited the highest recall (0.82) after optimisation, indicating strong sensitivity to severe accidents (Beyene et al., 2025).

The analysis reveals the importance of driver, environmental, and infrastructure factors in predicting accident severity. Driver age (mean: 44 years) emerged as the strongest predictor, while environmental factors such as nighttime on unlit roads increased fatal accident likelihood by 62% (Beyene et al., 2025). These findings underscore the need for targeted interventions addressing both behavioural and infrastructural risk factors.

The value of explainable AI for policy translation is demonstrated through Shapley Additive explanations (SHAP), which provide model interpretability and enable stakeholders to understand which factors most strongly influence predictions (Beyene et al., 2025). However, challenges persist regarding data quality, representativeness, and generalizability. The study acknowledges data limitations including underreporting, geospatial gaps, and the need for expanded model interpretability (Beyene et al., 2025). These challenges are particularly acute in LMICs, where over 90% of global road traffic fatalities occur yet data infrastructure remains underdeveloped (World Health Organization, 2024).

The integration of sensor networks and machine learning creates powerful synergies that exceed the sum of their parts. Sensor data serves as critical input for ML model accuracy, providing the real-time, high-frequency data necessary for robust predictive modelling (Beyene et al., 2025; Tsegaye, 2019). The WSN infrastructure enables continuous data collection on road conditions, railway infrastructure, vehicle health, and environmental factors—inputs that directly inform the ML models' predictive capabilities (Fenta et al., 2025).

Conversely, ML predictions enable proactive sensor-triggered responses. Rather than simply reporting conditions after they occur, the integrated framework uses predictive analytics to anticipate risks and trigger preemptive interventions (Beyene et al., 2025). This shifts corridor management from reactive to proactive; with ML models identifying high-risk conditions hours or days in advance, enabling targeted resource deployment before incidents occur.

The digital twin potential for scenario testing represents a significant opportunity for corridor management. Digital twins live digital representations of assets or systems can model, test, and optimize decisions in a virtual environment before real-world implementation (ScienceDirect, 2025). Sensor-informed generative digital twins that integrate real-world data from sensor networks can create high-fidelity scenarios and simulate rare and challenging transportation dynamics, serving as decision-support tools for policy evaluation, traffic efficiency strategies, and urban mobility planning (MDPI, 2025). For the Addis Ababa–Djibouti corridor, a digital twin could simulate port congestion, track rail and truck movements, predict delays, and test contingency plans before disruptions occur (LinkedIn, 2026).

b. Comparison with Existing Literature

The findings align with global ITS research while making unique contributions to the limited body of literature on intelligent transport systems in LMICs. The study confirms that ensemble methods, particularly Random Forest, consistently outperform traditional statistical approaches in accident severity prediction (Hamdan & Sipos, 2025), consistent with findings from other LMIC contexts including Jordan (Hamdan & Sipos, 2025) and Vietnam (ScienceDirect, 2026).

The research addresses identified research gaps in several ways. First, it provides a locally validated predictive framework for Ethiopia, addressing the gap in contextualised accident severity models for Sub-Saharan Africa (Beyene et al., 2025). Second, it demonstrates the feasibility of WSN deployment in resource-constrained environments, contributing to the limited evidence base on low-cost monitoring solutions for African transport corridors (Tsegaye, 2019; Fenta et al., 2025). Third, it integrates sensor and ML technologies in a unified framework, addressing the fragmentation that typically characterises ITS research in developing economies (Solomon et al., 2026).

The unique contributions to LMIC transport literature include: (1) validation of Random Forest as a robust, interpretable tool for policymakers in resource-constrained settings (Beyene et al., 2025); (2) demonstration of SMOTE's effectiveness in handling imbalanced accident data in an African context (Beyene et al., 2025); (3) quantification of key risk factors specific to Ethiopian conditions, including the 62% increase in fatal probability on unlit roads at night (Beyene et al., 2025); and (4) a replicable framework for sensor-ML integration that can be adapted to other developing-economy corridors (Tsegaye, 2019; Fenta et al., 2025).

V. Conclusions

Summary of Findings

This study set out to develop an integrated framework combining wireless sensor networks (WSNs) and machine learning for proactive safety monitoring and operational risk management on the Addis Ababa–Djibouti transport corridor. The findings confirm that the corridor, which carries approximately 95% of Ethiopia's trade, faces significant safety and operational challenges. Heavy goods vehicle accidents remain persistently high, with 6,914 HGV crashes recorded in 2024 alone (Ethiopian Federal Police Commission, 2024), while railway operations are constrained by outdated signalling systems that limit capacity to only two trains operating between stations.

The study validates wireless sensor networks as a low-cost, real-time monitoring solution for road and railway infrastructure. WSN deployment enables predictive maintenance, real-time anomaly detection, and capacity enhancement, allowing 3 to 4 trains to operate between stations simultaneously. Machine learning, particularly Random Forest, effectively predicts accident severity with 82% accuracy (AUC-ROC: 0.87), and the integration of SMOTE improved model performance from 78.6% to 82%. The SHAP explainability framework identifies driver age (average 44 years), nighttime conditions (increasing fatal probability by 62%), rainy weather, and road surface condition as key predictors of accident severity.

The integration of sensor networks and ML enables a fundamental shift from reactive to proactive risk management, transitioning from post-incident detection to real-time prediction, from scheduled maintenance to condition-based interventions, and from fragmented decision-making to coordinated, data-driven governance. The World Bank's USD 500 million Horn of Africa Initiative: Regional Economic Corridor Project , with additional USD 45 million approved in 2026 (World Bank, 2026), provides an enabling platform for framework implementation.

Contribution to Knowledge

This research makes several original contributions to academic knowledge and practical policy guidance. First, it presents the first integrated sensor-ML framework specifically designed for an African trade corridor, addressing the limited body of research on intelligent transport systems in low- and middle-income countries. Second, it provides context-specific validation of WSN and ML techniques in the Ethiopian setting, demonstrating the feasibility and effectiveness of these technologies in resource-constrained environments.

Third, the study establishes a practical evidence base for ITS policy in developing economies, quantifying key risk factors and demonstrating measurable performance improvements, 82% prediction accuracy, real-time detection, and 20-30% maintenance cost reduction. Fourth, the research offers a replicable methodology for corridor-level risk management that can be adapted to other developing-economy trade corridors across Africa, including the Northern Corridor (Kenya-Uganda-Rwanda) and the Central Corridor (Tanzania-Rwanda-Burundi).

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