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Study of the Technological Effects on the Implementation of the Railway Project in Burundi

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Abstract

Transport is a key driver of socio-economic development and a fundamental factor in improving living standards, particularly in African countries where mobility underpins access to markets, services, and opportunities. In Central Africa, road transport currently dominates both passenger and freight movements due to the limited performance of railway systems. However, the heavy reliance on road infrastructure, combined with its vulnerability to degradation and insufficient maintenance, constrains sustainable economic growth. In Burundi, road transport represents the backbone of the national transport system and plays a vital role in territorial integration, rural accessibility, and regional trade. Nevertheless, the current condition of transport infrastructure poses significant challenges that require timely and sustainable solutions. Rail transport, despite its strategic importance, remains underutilized in many African countries, accounting for less than 20% of total freight transport. This situation is mainly attributed to inadequate investment in infrastructure and the absence of effective institutional and regulatory frameworks. Yet, railways have strong potential to serve as a catalyst for economic development by reducing transport costs, improving reliability, and supporting large-scale trade and mobility. This study examines the technological impacts associated with the implementation of a railway project in Burundi, with the objective of enhancing economic growth, reducing transport delays, and promoting technological modernization. Particular emphasis is placed on the analysis of telecommunications and network coverage along the proposed railway corridor, which is essential for the deployment of modern railway systems, including signaling, monitoring, and safety technologies. By identifying existing connectivity gaps and technological constraints prior to project implementation, the study proposes practical solutions and recommendations to support an efficient, safe, and technologically integrated railway system. The findings contribute to informed decision-making and provide a scientific basis for the successful deployment of railway infrastructure as a sustainable alternative to road transport in Burundi.

Subject Areas

Applications of Communication Systems

Keywords

Speed Estimation Algorithm, Motion Sensors, Wireless Sensor Networks, 5G Telecommunication Network

1. Introduction

Burundi is a landlocked country undergoing a significant transition, with its economy primarily based on **subsistence agriculture**. This sector employs over 80% of the active population and accounts for the majority of the food supply. In recent years, the economic structure has seen little evolution. In fact, from 2019 to 2021, the agricultural sector's contribution to the GDP remained stable at 40%, while the shares of the services and industrial sectors also stagnated, averaging 42% and 18% respectively. This modest structural transformation, which results in an economy characterized by low-productivity agriculture and often informal services, makes the Burundian economy susceptible to shocks.

Burundi boasts a road network exceeding 11,000 km. According to the Office des Routes, this network comprises 4456 km of classified roads and 6150 km of unclassified roads.

Burundi is a member of four regional organizations: the Common Market for Eastern and Southern Africa (COMESA), the Economic Community of Central African States (ECCAS), the Economic Community of the Great Lakes Countries (CEPGL), and since July 2007, the East African Community (EAC). Most recently, a process has been initiated for integration into the SADC. Over the last decade, Burundi has strongly committed to EAC integration, modifying several of its laws and regulations to comply with the Community's rules, particularly concerning facilitation and customs. The EAC established a Customs Union in 2005 and a Common Market in 2010, allowing the free movement of people, goods, and capital. Since 2013, the community has also begun the process of creating a single currency.

For importing and exporting goods to or from the Port of Dar es Salaam, considered the closest and located over 1600 km away, Burundi currently has no other option than road transport. For its foreign trade, Burundi utilizes three main road corridors: The Northern Corridor (Bujumbura-Rwanda-Uganda-Kenya), primarily using roads, The Central Corridor, which includes two main routes: a road route (Bujumbura-Kobero-Dodoma-Dar es Salaam), and a combined lake/rail or lake/road route (Bujumbura-Kigoma-Tabora-Dar es Salaam), The Southern Corridor (Bujumbura-Mpulungu-Durban), using a combination of lake and rail or road transport. In addition to these, there's an alternative supply route via the Atlantic Ocean, known as the Western Corridor (Bujumbura-Kasai-Matadi-Atlantic Ocean), which uses road and the Congo River. While this route is currently very rarely used, it could represent a long-term option, especially for trade with the Americas. Currently, 80% of Burundi's international trade passes through the Central Corridor via Dar Salaam. Regarding electromagnetic wave coverage in Burundi, data collected from telecommunication operators indicates that 2nd Generation (2G) technology covers 92.10% of the territory. 3rd Generation (3G) coverage is at 38.12%, while 4th Generation (4G) coverage stood at 15.60% in 2023. The mobile phone penetration rate reached 66.02%, internet penetration was 22.9%, and mobile financial services penetration covered 17.33% in 2023. These figures highlight a very low coverage of 4th and 5th generation electromagnetic waves, according to the data source [1].

2. Methods and Materials

Within the framework of the railway project connecting Uvinza (Tanzania) to Gitega (Burundi), modern technologies are being considered to ensure the safety, efficiency, and precision of railway operations. One of the essential components of this system is the precise estimation of train speed, made possible by the installation of specific sensors.

Among the sensors likely to be used are:

- **Hall Effect Wheel Sensors**: These measure the rotational speed of axles by detecting variations in the magnetic field. They provide a reliable estimation of the train's speed and direction of travel.
- **Inertial Measurement Units (IMUs)**: Integrating accelerometers and gyroscopes, these provide continuous information on speed and position even in the absence of GPS, which is crucial in isolated or tunnel areas.
- **Optical Axle Encoders**: Used to precisely capture the rotational speed of wheels, particularly in automatic braking and traction control systems.
- **LiDAR Sensors**: Capable of measuring distance and scanning the environment, used in some modern lines to adjust speed based on obstacles or conditions.

In our academic research study on railway sensor systems, the distance between sensors and the communication protocols used depend on several factors, notably the type of sensor, the installation environment, and the specific requirements of the railway network.

The distance between sensors in railway systems varies according to their function and the technology used:

- **Onboard Speed Sensors**: These sensors, such as Hall effect sensors or optical encoders, are installed directly on the axles or bogies of trains. They measure the rotational speed of the wheels and are therefore spaced according to the mechanical configuration of the train, generally a few meters apart.

- **Ground-based Sensors for Infrastructure Monitoring**: These sensors, used to monitor the condition of rails, sleepers, or tracks, can be spaced from several hundred meters to a few kilometers apart, depending on the desired monitoring density and the communication range of the sensors. For example, one study showed that sensors could be spaced approximately 600 meters apart to ensure effective coverage.

2.1. Data

For the analysis of the technological impacts of the railway project in Burundi, a mixed-method research approach combining qualitative and quantitative techniques was adopted in order to ensure the collection of diverse, reliable, and accurate data. The study began with an extensive document review, including feasibility studies, academic research, and technical and policy documents related to railway infrastructure and telecommunications. This phase was essential for understanding the technological context of the project, its objectives, and the existing connectivity challenges. In parallel, official project reports and governance documents related to the implementation of the railway project were consulted to better grasp institutional and regulatory frameworks. Field data collection was carried out in the project area through surveys, consultations, and semi-structured interviews involving a total of 8 participants. These included two technical managers directly involved in railway and telecommunications project planning and supervision, two civil and telecommunications engineers with expertise in railway infrastructure, signaling, and network deployment, one technical staff from mobile network operators responsible for coverage and maintenance, one local administrative authorities overseeing infrastructure and territorial development, and two residents living in areas affected by the railway corridor. Experts and institutional stakeholders were selected using purposive sampling, while local residents were selected through simple random sampling to minimize bias. Semi-structured interviews and guided questionnaires were designed to allow both consistency and flexibility in data collection. Key questions addressed the types of technologies integrated into the railway project, including signaling systems, sensors, and communication networks; the influence of the railway project on the expansion or upgrading of telecommunications infrastructure; technical challenges related to mobile network coverage along the railway corridor; and mechanisms for data transmission to ensure railway safety and operational monitoring. Mobile network operators were specifically asked about current levels of 2G, 3G, and 4G coverage, network densification needs, signal propagation constraints near railway infrastructure, and future technological upgrade plans. Local authorities provided insights into regulatory coordination, institutional challenges, and the contribution of the railway project to local digital development, while residents were asked about their access to mobile and internet services, perceived changes in network quality, and expectations regarding technological improvements resulting from the project. Direct observation complemented interview data by allowing the identification and monitoring of technological installations along the railway line, including speed sensors, control points, and areas served by mobile networks. Spatial analysis was conducted using QGIS to produce detailed maps of mobile network coverage (2G, 3G, and 4G) along the railway corridor, enabling visualization of spatial disparities in connectivity. This analysis was further supported by data collected through specialized applications such as CellMapper and OpenSignal, which helped assess the quality and strength of mobile network signals in the affected areas. According to the Telecommunications Regulation and Control Agency of Burundi, mobile telecommunications in the country rely mainly on second-, third-, and fourth-generation technologies; however, their availability varies significantly across regions, as reflected in the coverage maps [2]. Overall, this integrated methodological framework enhances transparency, strengthens the reliability of the findings, and provides a solid basis for assessing the technological impacts of the railway project in Burundi.

Table 1 shows the analysis of mobile network coverage in Burundi, which highlights a significant disparity between the technological generations currently available. 2nd Generation (2G) remains the most widespread throughout the country, boasting a geographical coverage of 92.10% and an estimated reach of 96.8% of the population. 3rd Generation (3G) offers faster internet access and data services, but its coverage remains limited, extending to only 38.12% of the national territory. However, it reaches 50.6% of the population, indicating that 3G infrastructures are primarily located in densely populated urban areas where the demand for internet services is higher. 4th Generation (4G) is a crucial technology for mobile broadband and contemporary services such as video streaming or real-time tracking systems (like those used for trains or vehicles), yet its coverage remains very restricted. It covers only 15.60% of Burundian territory and approximately 32.18% of the population.

Table 1. Electromechanical wave coverage in Burundi.

Technologies	Geographical coverage	Population coverage
2nd Generation (2G)	92.10%	96.8%
3rd Generation (3G)	38.12%	50.6%
4th Generation (4G)	15.60%	32.18%

The data reveals a high concentration of population in certain municipalities, as shown in **Table 2** in this section. Gitega commune, with 182,096 inhabitants, is located in Gitega province, which is the most populous on this list. In the Rutana area, localities such as Musongati (62,203) and Mpinga-Kayove (62,053) show significant density. Finally, Makamba province includes Kayogoro, one of the most populated communes, with 104,028 inhabitants. These figures are essential for identifying the densest communes through which the railway will pass [3].

Table 2. Population of the municipality passes through the railway.

Municipalities	Population	Provinces
Rutana	1823	Rutana
Gitega	182,096	Gitega
Makebuko	69,847	Gitega
Itaba	60,077	Rutana
Musongati	62,203	Rutana
Mpinga-Kayove	62,053	Rutana
Giharo	52,980	Rutana
Bukemba	41,670	Makamba
Kayogoro	104,028	Makamba

The map (Figure 1) illustrates the Burundian provinces affected by the railway project in pink, clearly indicating the planned route. The provinces traversed are: Makamba, Rutana, and Gitega. This route shows a south-to-center orientation of the country, connecting strategic areas in terms of trade, agriculture, and regional mobility [4]. The choice of this railway corridor reflects a desire for regional integration between Burundi, Tanzania, and potentially the Democratic Republic of Congo (DRC), while also stimulating the economic development of the provinces concerned. This project could also improve Burundi's internal connectivity, reduce transportation costs, and strengthen commercial exchanges.

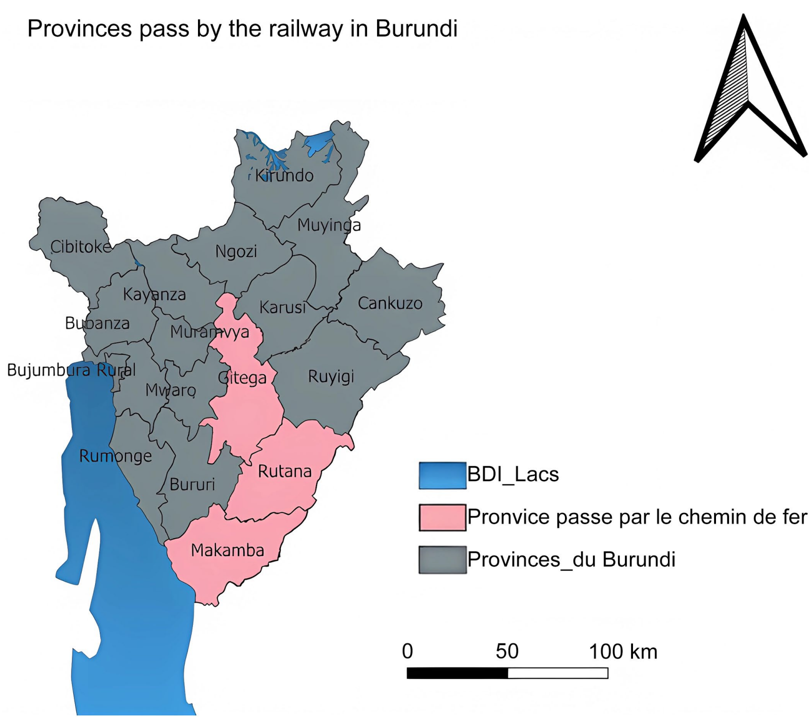

Figure 1. Provinces traversed by the railway project in Burundi.

2.2. Data Collection Techniques

The data used in this study was collected through interviews with the project team lead based in Burundi, as well as representatives from the Ministry of Finance, Budget, and Economic Planning; the Ministry of Trade, Transport, Industry, and Tourism; and the Ministry of Infrastructure, Equipment, and Social Housing. Additionally, Geographic Information Systems (GIS) were used to identify the provinces and communes affected by the railway route. An in-depth literature review was conducted, drawing from official reports, technical studies, and specialized publications. This was supplemented by consulting online databases from national and regional institutions, which provided information on infrastructure, population, and network coverage. Finally, technology watch allowed for the integration of data on sensor and communication systems used in similar railway projects in the region.

2.3. Methods

The study on the technological effects of the railway project in Burundi is based on a methodological approach combining geographical analysis tools, technical data, and documentary sources.

Firstly, geospatial maps were used to identify the provinces and communes affected by the railway route. These maps, derived from Geographic Information Systems (GIS), allowed for the establishment of the territorial boundaries crossed by the future line, as well as the direct influence zones of the project. Secondly, a documentary analysis was conducted using government reports, feasibility studies, academic publications, and sources from regional organizations (such as the East African Community or the African Development Bank). This analysis helped assess the economic, social, and environmental implications of the project. Furthermore, the study incorporates technological modeling aimed at evaluating the planned devices for train speed estimation. This includes the analysis of track sensors, railway communication protocols, and mobile network coverage essential for the proper functioning of these systems. A regional comparative analysis was also carried out to position the Burundian project within the broader context of railway integration in East Africa, particularly through projects in Tanzania and the Democratic Republic of Congo. This comparison helps identify the strengths and weaknesses of the national project. Finally, an impact mapping was performed, combining territorial, technological, and demographic data. This allowed for visualizing the affected areas, the potential benefits for local communities, and the accessibility and communication challenges in certain rural regions.

2.4. Materials

The selection of multiple train speed estimation methods in this study is motivated by the need to ensure accuracy, reliability, and operational continuity under diverse environmental and infrastructural conditions along the Uvinza–Gitega railway corridor. Since this railway will cross Burundi for the first time, it is essential to adopt a robust and redundant approach that can function effectively in open areas, urban sections, isolated zones or areas with limited satellite visibility.

Axle-based speed estimation: using Hall Effect sensors constitutes the core method of speed measurement in the proposed system. These sensors provide highly accurate and real-time measurements by detecting wheel rotation directly at the axle level. Their reliability, independence from external signals, and proven use in railway applications make them particularly suitable for safety-critical functions such as train control, braking systems, and signaling. This method was therefore selected as the primary reference for speed estimation.

GPS-based speed estimation: is included as a complementary method due to its ability to provide absolute positioning and velocity information over long distances. GPS data is especially valuable in open and rural sections of the railway, where satellite visibility is high. In addition to speed estimation, GPS contributes to train localization, route tracking, and synchronization with centralized traffic management systems. However, because GPS signals can be degraded, dense vegetation, or urban environments, it cannot be relied upon as a standalone solution.

Inertial Measurement Units (*IMUs*) are incorporated to ensure continuity of speed estimation when GPS signals are unavailable or unreliable. By integrating accelerometers and gyroscopes, IMUs enable short-term speed and position estimation through dead-reckoning techniques. Although IMU measurements may drift over time, they are highly effective when used in combination with axle sensors and GPS data, particularly in isolated sections of the network.

The logarithmic and model-based estimation approaches presented in this section are intended to enhance system robustness by smoothing sensor noise, compensating for measurement uncertainties, and providing fallback estimations in the event of partial sensor failure. These models allow for data fusion and error correction, improving the overall reliability of the speed estimation process.

In the proposed integrated system, data from axle sensors, GPS receivers, and IMUs are combined through a sensor fusion algorithm implemented within the onboard train control unit. Axle sensor data serves as the primary input, GPS data provides absolute reference and validation, and IMU data ensures continuity during signal outages. The logarithmic and analytical models are used to cross-check measurements, detect anomalies, and maintain stable speed estimation in real time. This multi-sensor architecture ensures a functional, resilient, and safety-compliant speed estimation system adapted to the operational and geographical conditions of the Burundi railway network.

2.4.1. Logarithm for Train Speed Estimation in the Study Area

In the context of the impact study on the railway project, a train speed estimation algorithm is necessary to contribute to accident reduction in this area, especially since some of the population in this zone are unfamiliar with this new mode of transport technology. To estimate train speed, it is often necessary to have experimental data or sensors that measure the distance traveled and the time elapsed. We propose a logarithmic formula that could be used to estimate speed based on these two points:

If we wish to introduce an exponential model (which could be useful for specific braking or acceleration situations on the ground), we can integrate a natural logarithm into the speed formula to account for adjustments in engine efficiency or variations in rail incline. We could then define an equation of the type:

$$\textbf{From } v(t) = v_0 \times \ln\left(1 + \frac{t}{T}\right)$$

v_0= initial train speed (in m/s);

t = elapsed time (in seconds);

T = a time constant representing the train's acceleration or braking period (in seconds); ln = natural logarithmic function (base e logarithm)

Distance and Time Data: To apply this logarithm, it is necessary to measure the distance traveled and the travel time between the different sensors installed on the rails.

Practical Estimation: Once the initial values $\mathbf{v_0}$, T, and t are collected from real train data, it will be possible to adjust the values so that the model can realistically reflect the situation on the ground.

To use this approach in Burundi for train speed estimation, the specific characteristics of the railway lines must be considered:

- **Terrain Slope**: An ascending or descending slope will influence the train's actual speed.
- **Weather Conditions**: In case of rain or humidity, the rails can be slippery, which affects speed.
- **Train Type**: Speed can also depend on the train model (high-speed train, freight train, etc.).

1) Method 1: Based on Axle Sensors

This is the most direct and often the most precise method in the short term.

Data Acquisition: Read the frequency or number of pulses from the axle sensors per unit of time.

Speed calculation

Is: $V = \omega \cdot R_{\text{eff}}$.

From where V is the speed, ω is the angular velocity of the wheel and Reff is the effective radius of the wheel.

If the sensor provides pulses per revolution,

$$V = \frac{\text{Number of pulses per second} * \text{Number of pulses per second}}{\text{Number of pulses per revolution}}$$

Potential problems: Wheel slip (slipping or skidding), wear on the wheels modifying Reff.

2) Method 2: Based on GPS

Useful for the position and speed validation of axle sensors. Data acquisition: Obtain GPS coordinates (latitude, longitude) and time at regular intervals.

Speed calculation:

$$V_{\text{GPS}} = \frac{\Delta d}{\Delta dt}$$

from where Δd is the distance traveled between two GPS points and Δdt is the time interval. Most modern GPS modules directly provide a speed estimate (ground speed). Potential problems: Variable accuracy depending on signal quality, latency, and less accurate estimation at very low speed or in case of signal loss (tunnels, heavily wooded areas).

3) Method 3: Based on Accelerometers

To estimate speed changes.

Data acquisition:

Measure the longitudinal acceleration a_L of the train.

Integration of acceleration: $V_t = V_{t-1} + a_L \cdot \Delta T$

4) Method 4: Based on Passage Sensors

For a punctual verification of the speed, we rely on three points in particular:

Preparation: Install sensors at known kilometric points or fixed intervals along the track.

Detection: Record the start and end time of the train at each sensor.

$$V = \frac{\text{Distance between two sensors}}{\text{Passage time between the two sensors}}$$

Predictive Model and Adaptation to Conditions

A predictive model can complement measurements to estimate future speed or detect anomalies.

Rolling Resistance Model: This model takes into account the train's mass, track gradient, air resistance, axle friction, etc.

$$F_{\text{Traction}} - F_{\text{Resistance}} = M \cdot a$$

where:

- F_{Traction}: is the locomotive's traction force;
- $F_{\text{Resistance}}$: is the sum of resistances;
- M: is the mass of the train;
- a is the acceleration.

This model can also be used to estimate the train's length.

Potential Problems: It only provides a spot speed measurement and requires infrastructure along the tracks.

- **Anomaly Detection:**

The integration of smart sensors aims to enhance safety, reliability and efficiency in railway operations. These sensors are designed to detect different types of hazards that may affect the operation of the railway system. Risks related to train dynamics, such as overspeed, abnormal variations in speed, wheel slip or inconsistencies between axles are monitored through on-board sensors, including Hall effect sensors and inertial measurement units (IMU). Furthermore, the condition of the railway infrastructure is monitored using sensors capable of identifying deformations in the rails, with misalignment contributing to the prevention of accidents related to track degradation.

Environmental conditions, such as floods, landslides, temperature variations and the presence of obstacles on the track, are also major sources of danger, particularly in the geographical context of Burundi. These risks are taken into account by hydrometric, thermal, and optical sensors. In addition, failures of electrical systems, communication, including power cuts, signal losses or electromagnetic interference are monitored to ensure data continuity and the proper functioning of control systems.

- **Model Algorithms**

For safety reasons concerning property and people, we are designing an intelligent algorithm based on data detected along railway tracks.

The algorithm (Figure 2) has been designed to brake the train in case a danger is detected on the tracks. The primary objective is to protect train safety by lowering their speed when a threat is identified on the rails. Here's how the algorithm works: It evaluates data coming from sensors capable of detecting obstacles or dangers on the track, then it confirms if a danger has been identified. As soon as the system perceives a danger, it adjusts the train's speed to a safe level. If no risk is identified, the system maintains the train's current speed. After either detecting a risk or maintaining the same speed, the system momentarily pauses its operation for one second before resuming the evaluation of information provided by the sensors. This process repeats in an infinite loop, ensuring constant monitoring and a rapid response in case of danger. Recall that this algorithm will be deployed to deal with dangerous situations such as objects on train tracks and landslides.

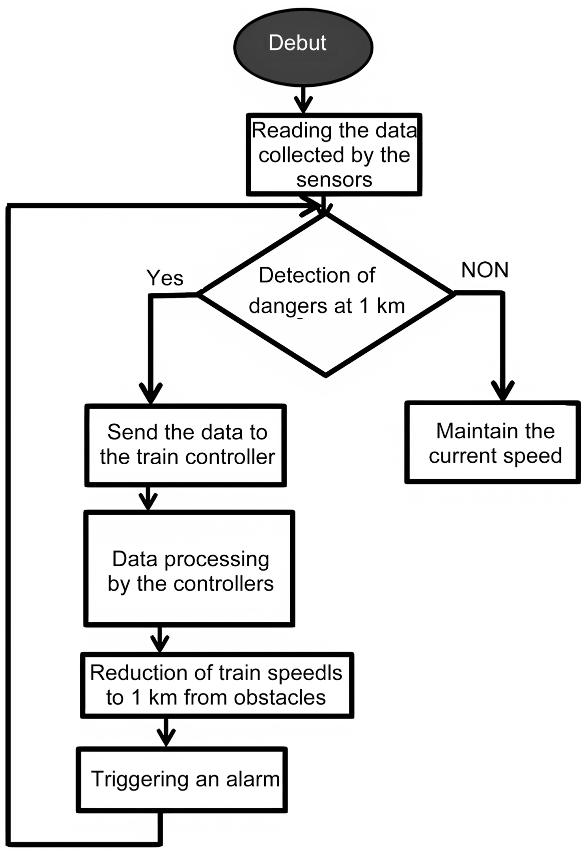

Figure 2. Algorithm of detected the track.

Figure 3 shows the simulation results of our algorithm 2. As soon as a danger is detected at a distance of 1 km, the system automatically transmits the information to the train's engine controller, which analyzes it, reduces the train's speed, and activates an alarm. This system will help prevent accidents by responding quickly to an identified threat on the tracks.

```
Début (Start)
Simuler la détection de danger à 1 km? (OUI/NON) : oui
OUI - Danger détecté à 1 km.
   -> Envoi des données au contrôleur de moteur de train...
   -> Envoi des données au contrôleur de moteur de train pour traitement...
   -> Vitesse réduite à 1 km du danger.
   -> ALARME DÉCLENCHÉE !
------------------------------
```

Figure 3. Showing the simulation results of Algorithm 2.

2.4.2. Technological Impacts of the Railway Project

The implementation of a railway project in Burundi will have significant repercussions on the traversed localities, both technologically and socially. These impacts can be both positive and negative, depending on how the infrastructure is integrated into the regions concerned. The project area currently benefits from good GSM network coverage, primarily thanks to Lumitel and Econet Leo. According to surveys conducted, communication in these areas is therefore ensured by mobile phones.

Figure 4 illustrates the transit areas for the railway project connecting Tanzania, Burundi, and the Democratic Republic of Congo (DRC), representing a major strategic advancement for economic and logistical integration in the Great Lakes region. As shown on the map, this railway line originates from the Port of Dar es Salaam in Tanzania, passes through key cities such as Kigoma, Gitega, and Bujumbura, and then extends to Kindu and other areas in eastern DRC. This interconnected rail network, linking with road and river routes, primarily aims to open up landlocked countries like Burundi and certain regions of the DRC, thereby facilitating access to regional and international markets. The project is also expected to reduce freight transport costs, particularly for agricultural, mining, and industrial products. Furthermore, it will stimulate cross-border trade by improving the fluidity of exchanges among the three countries, and strengthen economic ties between the East African Community (EAC) member states and beyond [5].

2.4.3. Positive Technological Impacts

According to the document related to the railway project in Burundi [6], and information provided by the Regulatory and Control Agency of Telecommunications (ARCT), the technological effects of the railway project in Burundi can be grouped into four main categories: Optimization of technological connectivity, integration of smart solutions in the transport sector, creation of jobs and skills development, and improvement of skills.

- **Optimization of Technological Connectivity**

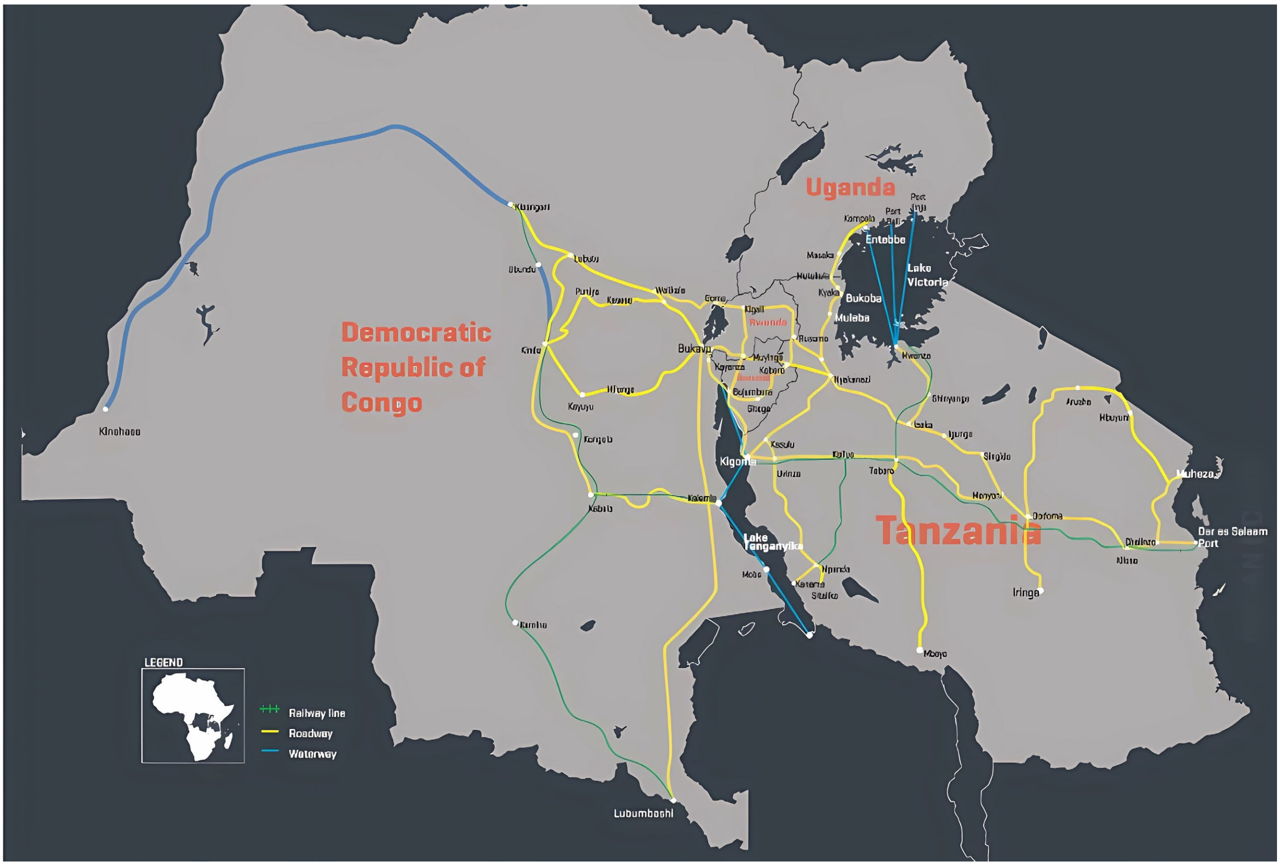

Figure 4. Countries traversed by the railway section (Burundi, Tanzania, DRC).

One of the primary benefits of the railway project will be improved connectivity in the localities it traverses. The establishment of new railway infrastructure will also lead to the deployment of advanced technologies such as train tracking sensors, sophisticated communication systems, and, in some cases, the extension of 5th Generation (5G) mobile network coverage. This will allow several rural areas to benefit from better connectivity and easier access to the internet and digital services.

➢ **Integration of Smart Solutions in the Transport Sector**

The project will facilitate the introduction of modern control and monitoring systems, such as sensors to measure train speed and automated railway traffic management systems. These cutting-edge technologies will promote the modernization of local infrastructure and improve transport management.

➢ **Job Creation and Skills Development**

The installation and maintenance of the new railway infrastructure require specialized technical skills. This project will create new jobs for inhabitants/youth in the traversed localities, particularly in the technology and equipment maintenance sectors. This transfer of skills can also benefit the local population, especially young people who will receive specialized training [7].

➢ **Skills Development and Enhancement**

Improved connectivity, particularly in rural areas, will foster access to digital services such as e-commerce, mobile banking, and online administration. This can stimulate the local economy, reduce digital isolation, and facilitate access to a range of modern services, even in remote regions.

2.4.4. Negative Technological Impacts

The negative impacts in the implementation of the joint project are numerous, notably:

- **Disruption of Existing Mobile Networks**

One of the risks associated with the implementation of new railway infrastructure along the railway section (Rutana-Makamba-Gitega) is the disruption of mobile phone signals, leading to a reduction in monthly revenues for telecommunication operators (such as mobile money services like Eco-cash, Lum-cash, phone calls, sending and receiving SMS, etc.). In particular, railway installations, such as bridges and stations, can interfere with existing cell towers and equipment, thereby creating areas of poor coverage or connection problems.

- **Inequalities in Technology Access Between the Three Countries**

Although the project will improve connectivity in certain areas, localities situated outside the railway route may not benefit from the same technological advancements. This could lead to a digital divide, where only regions close to railway infrastructure will be served by modern technologies, thus widening the gap between urban and rural areas.

- **Dependence on Imported Technologies**

The installation of sophisticated technologies from abroad could make the localities dependent on imported technological solutions, the maintenance of which could be costly and difficult to ensure in the long term. The lack of local training could also make autonomous management of equipment difficult in the event of failure or the need for updates.

- **Cybersecurity Risk and Technological Vulnerabilities**

The introduction of automated control systems and advanced technologies in the railway sector could expose the infrastructure to hacking risks or technical failures if they are not protected by robust cybersecurity protocols. Malicious attacks could disrupt not only railway operations but also associated communication networks.

Figure 5 displays the precise route of the projected railway in Burundi, highlighting the communes it traverses in light grey. It can be observed that the railway infrastructure connects several strategic communes in the provinces of Makamba, Rutana, and Gitega, thus crossing the heart of the country from south to center.

This route demonstrates an effort towards economic and logistical integration, by facilitating the mobility of goods and people between agricultural production zones and national/international markets. It also aims at the valorization of rural communes, often landlocked, which will benefit from improved access to transport infrastructure, as well as better interconnection with neighboring countries, particularly via the Central Corridor [7].

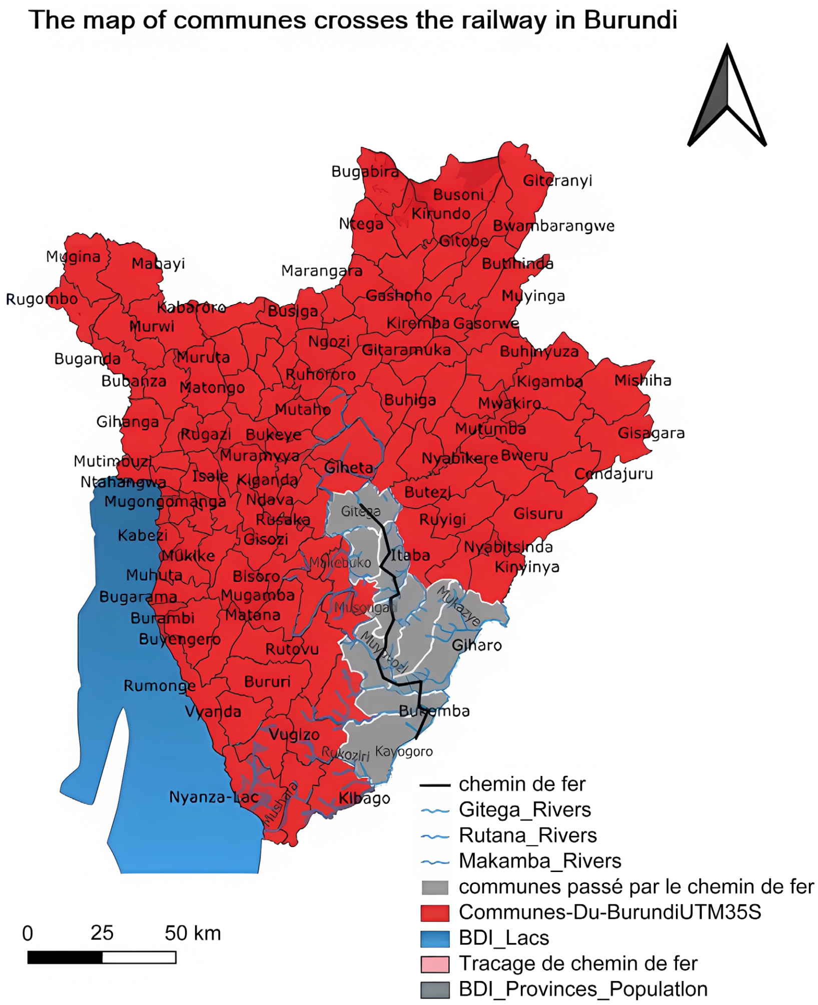

Figure 5. Communes traversed by the railway project in Burundi.

Figure 6 marks a strategic regional infrastructure of significant scale. The route shows that the line connects several Burundian communes (including Gitega, Itaba, Mpinga-Kayove, Rutana, Bukemba, Kayogoro) to the Tanzanian border, then continues towards key areas in Tanzania, notably Kabanga, Kasulu, Manyovu, Kigoma, Tabora, and finally to Isaka. This project enables significant regional integration by linking the heart of Burundi to Tanzania's existing railway networks (particularly the SGR: Standard Gauge Railway) [8].

3. Results and Discussion

The study conducted on the railway project in Burundi, specifically on the section connecting Gitega, Rutana, Makamba, and the Tanzanian border, has yielded several significant results from technological, socio-economic, and territorial perspectives. Geographical Coverage and Mobile Network in the Study Area: The area traversed by the railway project has uneven mobile network coverage. The provinces of Makamba and Rutana, although crossed by the project, still have low 4G coverage, representing only 15.6% of the national coverage. This poses

Figure 6. Map presents the planned railway section between Burundi and Tanzania.

communication challenges for intelligent systems. Potential for Integrating Wireless Sensor Networks: In areas poorly covered by cellular networks, the study demonstrated the relevance of WSNs (Wireless Sensor Networks) for monitoring railway infrastructure. The communes concerned by the railway line (Makebuko, Itaba, Mpinga-Kayove, Giharo, Bukemba, Kayogoro) will benefit from improved communication infrastructure if technologies like LoRa with an 868 MHz bandwidth are implemented. The introduction of simulators like NS-3 allowed for the virtual evaluation of the performance of wireless sensor networks along the railway. These tools showed that the interconnection of sensors remains viable over significant distances in rural areas.

3.1. Communication and Sensor Network in Railways

In the context of railway development in Burundi, the establishment of a reliable communication system is a major challenge, especially in rural areas with limited coverage by conventional telecommunications networks [9]. Wireless Sensor Networks (WSNs) offer a suitable solution to ensure the continuous transmission of critical data related to railway infrastructure monitoring [10]. The choice of NB-IoT and LwM2M protocols is based on their adequacy to the technical, energy and economic constraints of the Burundian context. The NB-IoT protocol stands out for its wide range, low power consumption and ability to connect a large number of sensors over long distances, reducing the need for additional infrastructure. It is particularly suitable for the transmission of small volumes of data generated by railway sensors and allows autonomous operation of devices for several periods, an essential asset in areas difficult to access. The combination of NB-IoT for connectivity and LwM2M for application management thus constitutes a robust and efficient architecture, meeting the requirements of coverage, reliability, low energy consumption and cost control. This approach allows real-time monitoring of the railway infrastructure and represents a technologically and economically relevant solution for the sustainable development of the Burundian railway network. And HTTP/HTTPS, thereby facilitating improved long-distance communication and the creation of an autonomous mesh network [11]. Data transmission between one point and another on the railway is done in unicast mode. Thanks to this technology, collected information is transmitted to local/remote processing units, enabling rapid alerting of responsible parties in case of a malfunction or potential danger [12]. The detection of a train's speed can be achieved by calculating the time it takes to pass between two sensors spaced at a known distance, according to the following equation: $V = d/\Delta t$, where d is the distance between the sensors and Δt is the transit time.

Figure 7 illustrates the effectiveness of the sensor network installed along the railway line. It is observed that the communication quality (successful transmission rate) remains constant in the clear areas shown on the map, while it degrades slightly in wooded or mountainous regions. Transmission delays (latency) generally remain low, below 200 ms, which ensures good system responsiveness in case of obstacle detection or abnormal situations. The longevity of the sensors, presented according to their location, reveals faster wear in high-traffic areas, indicating that more regular replacement might be necessary or that integrating solar energy solutions would be advisable. In summary, the network performs well, but energy optimization and more homogeneous coverage are necessary to ensure uninterrupted communication, which is essential for railway safety.

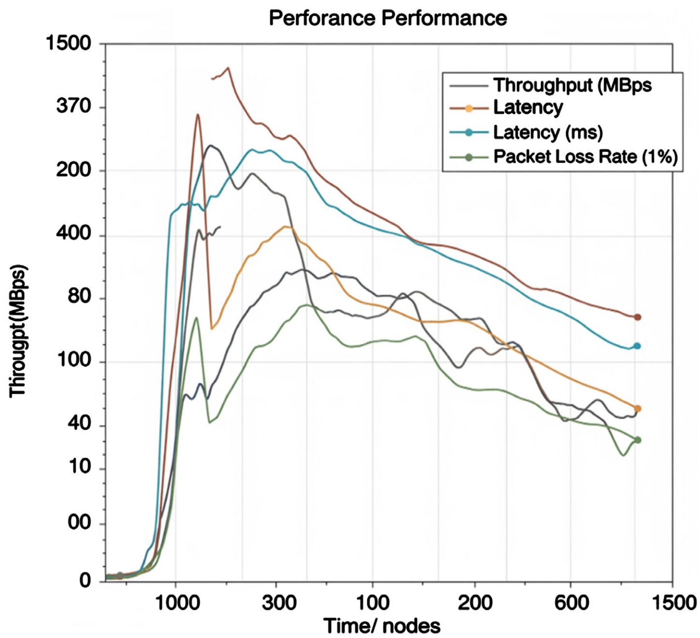

Figure 7. Performance graph of wireless sensor networks along the railway.

3.2. Some Suggestions

In countries like Burundi, where 4th and 5th Generation network coverage is less deployed, which hinders communication and the implementation of joint projects between the three countries, it is strongly recommended to integrate modern technologies from the planning and implementation phase. The use of wireless sensor networks will enable real-time monitoring of the condition of rails, trains, and infrastructure, thereby reducing the risk of technical incidents and facilitating preventive maintenance. Furthermore, the establishment of adapted railway communication systems such as GSM-R or low-bandwidth technologies like LoRa can ensure better coordination between different control posts, even in rural areas with low network coverage. It is also crucial to strengthen the training of local stakeholders on the use of these technologies, and to plan for an improvement in digital connectivity along the traversed areas. These recommendations aim to guarantee optimal, secure, and sustainable operation of the railway network, while fostering local ownership and technological innovation.

4. Conclusion

The railway project connecting Uvinza (Tanzania) to Gitega (Burundi) represents a major step forward for Burundi's economic development and regional integration. This electrified standard-gauge railway corridor aims to facilitate the transport of goods and passengers, thereby reducing logistical costs and transit time to the port of Dar es Salaam. The study analyzing the technological impacts highlights the importance of integrating innovations such as wireless sensor networks, modern railway communication systems, and digital tools to optimize the management, safety, and efficiency of rail transport. However, challenges remain, particularly regarding connectivity in rural areas and technical training for local personnel. The development of the railway in Burundi is not just an improvement in transport infrastructure, but also a lever for national technological innovation. For its impact to be sustainable, it is essential to integrate technological solutions adapted to the local context, strengthen the capacities of the involved stakeholders, and ensure close collaboration between the public and private sectors. By focusing on technology, the country can transform this project into a driver of economic and social progress.

Conflicts of Interest

The authors declare no conflicts of interest.

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