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ScienceDirect

Procedia Computer Science 236 (2024) 493–501

Procedia Computer Science

www.elsevier.com/locate/procedia

International Symposium on Green Technologies and Applications (ISGTA'2023)

Intelligent transport systems for green transformation of transport corridor

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Abstract

The sustainable evolution of international transport corridors is imperative to meet the dual challenges of growing global transportation demands and pressing environmental concerns. This paper delves into the potential of Intelligent Transport Systems (ITS) as a transformative tool to achieve the green objectives set for international transport corridors. Drawing from systems theory, in the paper a mathematical framework to model the nexus between conventional transport mechanisms and green transformation goals is proposed. Paper describes taxonomy of main directions for ITS oriented on green transformation of transport corridor and roadmap of such transformation.

Keywords: **Green transport corridors; intelligent transport systems; sustainability; modeling**

1. Introduction

In an age marked by urbanization and technological evolution, transport corridors have emerged as essential facilitators of global exchange. However, as environmental concerns intensify, there's an urgent call to infuse these corridors with sustainability. This shift is envisioned through Green Transport Corridors (GTC), underpinned by the capabilities of Intelligent Transport Systems (ITS). Traditional corridors, vital for global interactions, often face

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1877-0509
10.1016/j.procs.2024.05.058

environmental and efficiency challenges. By seamlessly integrating ITS into GTC, we can harness technologies such as advanced sensors, data analytics, and automation to reimagine these pathways. This paper delves into the potential of ITS within GTC, charting a course towards a greener, more efficient transport future. Structure of the paper: section 2 – related works, section 3 – concept of green transport corridor, section 4 – ITS role in the green transformation of the international transport corridors, section 5 – model of transport corridor green transformation, section 6 – roadmap of transport corridor green transformation, section 6 – discussion, section 7 – conclusion.

2. Related works

The establishment of international transport corridors (ITC) hinges on meticulous planning and design. Scholars and practitioners have increasingly employed mathematical formulations to address the complexity inherent in ITC design. This literature review encompasses key works that highlight the mathematical underpinnings and methodologies in ITC design.

The study [1] addresses the multimodal discrete network design problem, focusing on optimizing car, bus, and rail systems with inter-modal transfers via walking and bike-sharing. Utilizing a proposed bi-objective programming model and a hybrid heuristic algorithm, the research evaluates effectiveness through tests on both a basic and an actual transport network.

A three-phase disjoint-path framework to increase network availability, addressing limitations in equal-cost multipath routing is introduced in study [2]. Through optimizing multipath solutions, dividing paths, and assessing robustness, the framework ensures effective load balancing and meets diverse service needs.

The research [3] focuses on optimizing cargo flow within a digital transport corridor's node, using a mathematical model for decision-making in the Warehouse Management System software.

The model using Data Envelopment Analysis to determine the optimal green transport route by considering external socio-ecological costs, transport costs, and transport time is discussed in [4].

The methodology to assess and rank the performance of railway networks along the Trans-European Transport Network, specifically the Orient–East Med corridor, using twenty-two infrastructural, economic, and technological criteria is described in [5]. This methodology can guide transport planning decisions for enhanced connectivity and sustainability.

The paper [6] presents a systematic literature review on the methodological perspectives of cost-benefit analysis (CBA) for road infrastructures. The study proposes a conceptual framework for more accurate CBA modelling in a microeconomic, probabilistic, and dynamic environment.

The bibliometric review of efficiency analysis in transportation systems, focusing on data-envelopment analysis and, notably, stochastic frontier analysis publications is provided in [7]. The findings identify gaps like eco-efficiency and safety in rail research, and present a step-by-step methodology for data envelopment analysis in rail systems.

The article [8] evaluates the impact of new transport infrastructure on regional development in Central and Eastern European countries. The study proposes a dynamic spatial sequence connecting infrastructure investments with regional and metropolitan development.

Despite the extensive research literature on international green transport corridors, there remains a noticeable gap concerning the tangible positive impacts of Intelligent Transport Systems on their green transformation. While many studies highlight the conceptual benefits of ITS, comprehensive assessments detailing their direct contributions to sustainability in these corridors are limited. This gap underscores the need for more in-depth evaluations and empirical studies to understand fully the transformative potential of ITS in fostering a greener transportation landscape. This article is aimed at filling this gap.

3. Concept of green transport corridor

International GTC represent cross-border transportation routes optimized for environmental sustainability. Spanning multiple countries, these corridors prioritize eco-friendly transport modes, efficient infrastructure, and innovative technologies to reduce environmental impact.

GTC represent a paradigm shift in approach to transportation and logistics. While traditional transport corridors focus predominantly on facilitating the movement of goods and passengers efficiently, GTC extend this perspective by integrating environmental sustainability at the core of their operational ethos. They are not just routes or pathways but are holistic ecosystems that synergize infrastructure, technology, and sustainability practices.

Central to the GTC concept is the minimization of the environmental footprint. This is achieved through multiple avenues: the integration of renewable energy sources, the deployment of eco-friendly transportation modes, the establishment of green data centers, and the use of advanced monitoring and analytics platforms to ensure optimal environmental performance.

The detailed comparison of the traditional transport corridor and a GTC is shown in the Table 1.

Table 1. Comparison of traditional and green transport corridors.

Comparison Criteria	Transport corridor	Green transport corridor
Purpose	Primarily developed to facilitate efficient movement of goods and people. The focus is on reducing transit time and increasing transport capacity.	While still prioritizing efficient transport, a GTC is designed with an explicit focus on minimizing environmental impact and promoting sustainable practices.
Environmental Considerations	May or may not incorporate environmental measures. Environmental considerations are often secondary, driven primarily by regulatory compliance.	Prioritizes environmentally friendly infrastructure and operations. This includes reducing carbon emissions, using renewable energy sources, and protecting biodiversity.
Design and Infrastructure	Designed for functionality, emphasizing durability, capacity, and cost-effectiveness.	Designed with sustainable materials, incorporates green spaces, and includes infrastructure such as electric vehicle charging stations, bike paths, and pedestrian-friendly zones.
Digital and Technological Integration	Might include some digital components like basic traffic management systems.	Prioritizes advanced digital integration with tools like IoT sensors, data analytics platforms for environmental monitoring, and smart traffic management systems to reduce congestion and pollution.
Stakeholder Engagement	Engagement primarily with transport operators, construction contractors, and governmental bodies.	Involves a broader set of stakeholders, including environmental advocacy groups, sustainability experts, and community representatives advocating for minimal disruption.
Energy Sources	Relies on conventional energy sources for operations, such as fossil fuels.	Prioritizes renewable energy sources, like solar or wind power, and encourages the use of cleaner fuel alternatives.
Holistic Impact	Measures success predominantly based on efficiency, capacity, and cost metrics.	Assesses impact based on a balance of efficiency, environmental preservation, social benefits, and long-term sustainability.

Table 2. Main components of the GTC ecosystem.

Components of the GTC ecosystem	Brief description
Physical Infrastructure	This encompasses the tangible components such as roads, rails, bridges, tunnels, rest areas, and transit hubs. Designed with sustainability in mind, they utilize eco-friendly construction materials, renewable energy, and are built to cause minimal disruption to natural habitats
Digital Layer	Modern GTCs are entrenched in technology. Smart traffic management systems, real-time data analytics, IoT sensors, and digital communication platforms form the backbone, optimizing traffic flow, monitoring environmental impact, and ensuring efficient energy use.
Environmental Biomes	A GTC is inextricably linked with its environment. This includes the natural habitats it passes through, the flora and fauna it affects, and the larger ecological impact it has. Measures like wildlife crossings, green buffers, and pollution monitoring ensure the corridor coexists harmoniously with nature.
Renewable Energy Sources	Solar panels, wind turbines, and other renewable energy installations along the corridor not only power the infrastructure but also contribute to a broader sustainable energy grid, reducing reliance on fossil fuels.
Transport Modes	Vehicles, trains, bicycles, and pedestrians using the corridor are part of this ecosystem. The GTC promotes electric and hybrid vehicles, efficient public transport systems, and non-motorized transport, integrating them seamlessly.
Human Interactions	Local communities, travelers, maintenance workers, and officials interact with and within the corridor daily. Their activities, needs, and feedback are vital for the continuous evolution and optimization of the GTC.
Regulatory Framework	Policies, standards, and regulations guide the design, construction, and operation of the GTC. These ensure adherence to sustainability goals, safety standards, and ensure the corridor meets both local and international environmental benchmarks.
Economic Activities	Businesses, trade hubs, service stations, and logistics providers operating within or in proximity to the corridor influence and are influenced by the GTC's operations. Their practices, in turn, need to align with the green objectives of the corridor.
Research and Development	Continuous innovation is pivotal. Research institutions, universities, and tech companies might collaborate to pilot new technologies, materials, or practices in the GTC, ensuring it remains at the forefront of sustainable development.
Stakeholder Collaboration	NGOs, environmental agencies, transportation authorities, and other stakeholders actively collaborate to oversee, critique, and enhance the corridor's operations. Their diverse perspectives ensure a balanced and holistic approach.

While both types of corridors serve the fundamental purpose of facilitating transport, a GTC goes several steps further, integrating the principles of sustainable development into every aspect of its design, construction, and operation.

The GTC is not merely a physical infrastructure, but a complex, dynamic ecosystem that intersects economic, technological, environmental, and social spheres. To understand the ecosystem of the GTC, it's vital to delve into its multi-faceted components and their inter-relationships (Table 2.)

4. ITS role in the green transformation of the international transport corridors

The digital layer in the ecosystem of a GTC (Table 2) is of paramount importance, serving as the core component that optimizes and streamlines operations. Within this digital framework, ITS play a crucial role, harnessing real-time data analytics, sensors, and automation to enhance traffic flow, reduce emissions, and ensure safety. In essence, ITS acts as the brain of the digital layer, enabling adaptive, efficient, and sustainable operations throughout the corridor, thereby bridging the gap between eco-conscious goals and practical transport solutions.

The main components of digital layer in the GTC ecosystem on the base of ITS are shown in the Table 3.

Table 3. The main components of digital layer in the GTC ecosystem on the base of ITS.

ITS component of GTC	Functionality
IoT Sensors	Traffic Flow Sensors monitor vehicular movement, congestion levels, and traffic patterns in real-time. Environmental Sensors continuously monitor air quality, noise levels, and even water quality in adjacent natural bodies, ensuring that the corridor's operations don't cross environmental thresholds. Infrastructure Health Monitors. Embedded within the physical infrastructure, these sensors can detect early signs of wear, damage, or structural issues, facilitating timely maintenance.
Real-time Data Analytics Platforms	By processing data from myriad sources instantaneously, the GTC can respond to fluctuations in traffic volume, incidents, or adverse weather conditions, ensuring efficient corridor operations. Predictive analytics, powered by machine learning, can forecast potential issues or disruptions, allowing for preemptive solutions.
Smart Traffic Management Systems	These systems optimize traffic flow by dynamically adjusting signal timings, opening, or closing lanes, or even rerouting traffic based on real-time conditions. They can also communicate with connected vehicles, advising on optimal speeds, or alerting drivers to upcoming incidents.
Digital Communication Platforms	Variable message signs along the corridor can display real-time information, advisories, or warnings to drivers. Dedicated mobile apps or websites provide travelers with up-to-date corridor conditions, eco-friendly driving tips, or even the environmental performance of the corridor.
Energy Management Systems	By monitoring and analysing the energy consumption of the corridor's facilities and operations, these systems ensure optimal use of renewable energy sources. They can dynamically adjust energy distribution based on demand and source availability, ensuring maximum use of green energy.
Centralized Control Centers	Equipped with state-of-the-art digital dashboards, these centres act as the corridor's command hubs. Operators can monitor, control, and coordinate activities across the entire corridor from these centres. Integrated with emergency services, they can swiftly respond to incidents, ensuring safety and minimizing disruptions.
Integrated Ticketing and Payment Systems	For multimodal transport corridors, digital platforms allow users to plan, book, and pay for journeys that may involve multiple transport modes. Blockchain or similar technologies can be employed for transparent, efficient, and secure transaction systems.
Digital Feedback Mechanisms	Travelers, local communities, or businesses can provide real-time feedback or report issues via digital platforms, ensuring continuous stakeholder engagement and improvement.
Data Storage and Cloud Computing	Massive amounts of data generated need to be securely stored, processed, and retrieved. Cloud platforms offer scalability and flexibility, ensuring that the digital operations of the corridor are always agile and responsive.

The structure of an ITS based Green Transport Corridor control and monitoring center would be a fusion of advanced technological components, data-processing capabilities, and human expertise, all geared towards facilitating seamless, efficient, and sustainable transport. The taxonomy of ITS for GTC is shown at the Fig. 1.

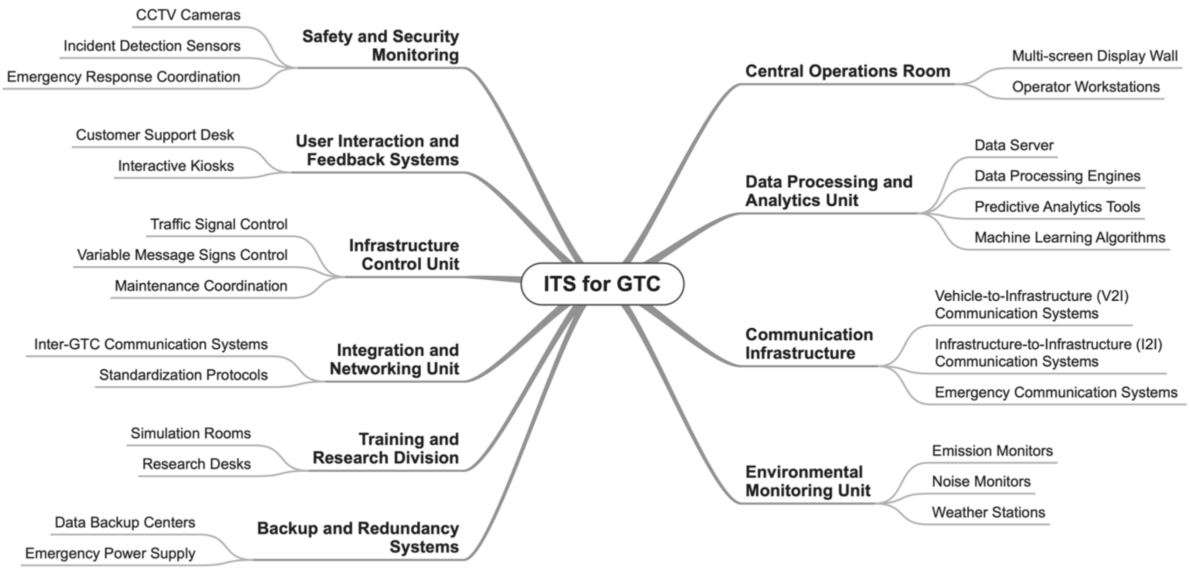

Fig 1. Taxonomy of ITS for GTC.

5. Model of transport corridor green transformation

The transition from a traditional Transport Corridor (TC) to a Green Transport Corridor requires the modification of certain system parameters and the introduction of new ones. Let's frame this transformation mathematically.

1. Defining the system:

Let $C = \{C_1, C_2, \dots C_n\}$ represent the components of a traditional transport corridor where □n is the number of national fragments.

Let $G = \{G_1, G_2, \dots G_n\}$ represent the components of the Green Transport Corridor.

2. Transformation function:

We need a function T that will map each component C_i to G_i, indicating the transformation of a traditional component to its green counterpart $T: C_i \rightarrow G_i$.

3. Parameters and metrics:

Traditional transport corridor might have parameters like:

P_{cost} - Cost of transport.
P_{time} - Time of delivery.
$P_{efficiency}$ - Efficiency of transport.

The GTC introduces new parameters like:

P_{carbon} - Carbon footprint.
$P_{renewable}$ - Percentage of renewable energy sources.
$P_{sustain}$ - Sustainability metrics.

These parameters are associated with weight factors indicating their importance:

$W = \{w_{cost}, w_{time}, w_{efficiency}, w_{carbon}, w_{renewable}, w_{sustain}\}$

4. Objective function:

For the transport corridor (TC): $O_{TC} = w_{cost} \times P_{cost} + w_{efficiency} \times P_{efficiency}$

For the GTC:

$$O_{TC} = w_{cost} \times P_{cost} + w_{efficiency} \times P_{efficiency} + w_{carbon} \times P_{carbon} + w_{renewable} \times P_{renewable} + w_{sustain} \times P_{sustain}$$

The transformation's goal would be to minimize O_{TC} while maximizing elements that make the GTC eco-friendly, effectively working to optimize O_{GTC}.

5. Constraints:

In the transformation process, certain constraints might be defined:

$$P_{carbon} \leq P_{carbom\_max}$$
$$P_{renewable} \geq P_{renewable\_norm}$$

where P_{carbom_max} is certain predefined threshold, $P_{renewable\_norm}$ is certain percentage.

6. Integration:

Integrating all national fragments to achieve a holistic Green Transport Corridor would involve optimizing the overall objective function:

$$O_{Total} = \sum_{i=1}^{n} O_{GTC_i}$$

where n is number of national segments of international green transport corridor.

In terms of systems theory, the process entails the reconfiguration of the existing system (TC) using a transformation function that adheres to new parameters and constraints, ultimately yielding a new system (GTC) with a greener, more sustainable focus. This mathematical framework offers a structured methodology for guiding and evaluating the corridor's green transition. Developing a mathematical model for a GTS with ITS requires the incorporation of both environmental and technological variables into a cohesive framework. This mathematical model would aim to optimize transport processes, ensuring the sustainability and efficiency of the GTS, while making the best use of the capabilities offered by ITS.

Let's provide the mathematical framework of the described GTS with ITS.

Given:

T – set of all transport modes in the transport system,
S - set of all sensors and ITS components,
R – set of all road segments or routes in the corridor,
$E_{t,r}$ - emission by transport mode t on transport segment r ,
$F_{t,r}$ - traffic flow rate of mode t on transport segment r ,
$V_{t,r}$ - speed of mode t on transport segment r ,
D_s - data reading from sensor s ,
C_t - carbon emission rate for transport mode t ,
M_t - maximum allowable traffic flow for mode t ,
$S_{t,r}$ - safety speed limit for mode t on transport segment r .

In this case we can use the next equations.

1. Emission:

$$E_{t,r} = C_t \times F_{t,r}$$

2. Traffic flow vs speed

$$F_{t,r} = \frac{\alpha_t}{V_{t,r} + \beta_t}$$

where α_t, β_t are constants related to mode t .

3. Sensor data and speed correlation

$$V_{t,r} = f(D_s)$$

where f is a function that relates sensor data to an optimal speed. This function can be determined empirically or through machine learning methods.

The objective function can be defined as minimization of the total emissions while ensuring traffic flow efficiency:

$$\min \sum_{t\in T}\sum_{r\in R} E_{t,r} - \lambda \sum_{t\in T}\sum_{r\in R}(V_{t,r} \times F_{t,r})$$

where λ is a weight that determines the trade-off between reducing emissions and ensuring flow efficiency.

There are some constraints in this model:

$V_{t,r} \leq S_{t,r}$ – Safety and legal speed limits,
$F_{t,r} \leq M_t$ - traffic flow constraints,
$D_s \leq D_{max_s}$ – sensor data constraints, where D_{max_s} is the maximum reading for sensor s ,
$\sum_{t\in T} E_{t,r} \leq E_{max}$ – emission constraints, where E_{max} is the maximum allowable total emission for the corridor.

This mathematical framework provides a foundation to represent the integration of GTS with ITS. Actual implementation would require further refinements, including specifying functions like $f(D_s)$ and fine-tuning the parameters and constraints based on real-world data and desired outcomes.

The objective defined in the model encompasses dual yet potentially competing goals – minimizing emissions while maximizing traffic flow efficiency along the transport corridor. An algorithmic approach can clarify the sequential optimization process:

1. Initialize parameters: Transport modes (T); Sensors and ITS components (S); Transport routes/segments (R); Emissions data (E); Traffic flow data (F); Other constraints and thresholds.
2. Deploy sensors and collect real-time data (D).
3. Apply machine learning models to correlate data to speed (V).
4. Compute emissions using carbon emission rates and traffic flow data.
5. Optimize traffic flow efficiency by adjusting speed limits, routes, etc.
6. Quantify objective function – emissions and flow efficiency.
7. Refine ML models and constraints to re-optimize.
8. Repeat step 2 onwards continuously.

6. Roadmap of transport corridor green transformation

Transforming a traditional Transport Corridor into a Green Transport Corridor in the technological domain necessitates the strategic adoption and integration of cutting-edge, eco-friendly technologies across various facets of the corridor's infrastructure and operations.

Here's a detailed technological roadmap for this transformation:

1. Digital Infrastructure Development:
   - Embed IoT devices for real-time monitoring of traffic, environment, and infrastructure health.
   - Establish eco-friendly data centers with renewable energy sources and efficient cooling systems.
2. Advanced Transportation Technologies:
   - Promote the use of EVs by developing charging infrastructure and incentives for EVs.
   - Integrate infrastructure to support biofuels, hydrogen fuel cells, and other sustainable fuel alternatives.
3. Intelligent Traffic Management:
   - Use AI-driven algorithms to optimize traffic flow, reducing idling time and emissions.
   - Predict traffic bottlenecks, enabling better route planning and congestion management.
4. Environmental Monitoring:
   - Deploy sensors to monitor real-time emissions along the corridor, aiding in pollution control.
   - Use advanced meteorological tools to monitor and predict weather patterns, assessing their impact on corridor operations.
5. Renewable Energy Integration:
   - Harness renewable energy sources, such as solar panels on buildings and wind turbines along the corridor.
   - Integrate advanced energy storage solutions to ensure consistent power supply, especially for critical infrastructure.
6. Sustainable Construction Technologies:
   - Optimize for sustainable construction materials like recycled or low-impact concrete and asphalt.
   - Use techniques like prefabrication or 3D printing to reduce waste and energy consumption during construction.
7. Waste Management & Recycling Systems:
   - Use sensor-equipped waste bins to optimize waste collection schedules and routes.
   - Implement advanced waste sorting and recycling technologies to maximize resource recovery.
8. Communication Technologies:
   - Deploy advanced communication networks for faster, real-time data transfer and decision-making.
   - Establish centralized digital control rooms to manage, monitor, and optimize the entire corridor ecosystem.
9. User-centric Technologies:
   - Develop applications that provide real-time updates, green route planning, and carbon footprint tracking for users.

- Use AI-driven chatbots or digital platforms to gather user feedback on corridor efficiency and eco-friendliness.

10. Continuous Technological Research & Innovation:
    - Allocate funds and resources for continuous research in green transport technologies.
    - Collaborate with tech companies, research institutions, and startups to explore innovative solutions for a greener corridor.
11. Technology Training & Upskilling:
    - Offer specialized training to corridor staff on new technologies and their sustainable applications.
    - Conduct regular workshops on emerging technologies in the green transport domain.

The transformation from a conventional Transport Corridor to a GTC from a technological standpoint is all about integrating state-of-the-art technologies that not only enhance operational efficiency but also prioritize environmental sustainability. This roadmap, with a focus on technology, offers a blueprint for creating a future-ready, environmentally responsible transport corridor.

7. Discussion

While this paper has focused extensively on conceptual frameworks and mathematical models for GTC integrated with ITS, the practical implementation of these sophisticated concepts warrants further analysis through empirical evidence and real-world case studies.

A prime example of an early-stage GTC leveraging ITS capabilities is the United Kingdom's Trans-Pennine Upgrade Programme [9]. This mega infrastructure project aims to upgrade rail connections between major Northern cities in the UK through a multi-billion-pound investment. Beyond mere transport upgradation, sustainability is a key focus, with ambitious targets set for carbon reduction. IoT sensors across the route will monitor real-time emissions, solar panels will power signaling systems, and hyper-efficient trains will ply the tracks. This project exemplifies how a data-driven, optimized transport ecosystem can be engineered through ITS integration.

Singapore's approach to intelligent mobility also holds valuable lessons for large-scale adoption. Their Smart Mobility 2030 plan uses enormous amounts of sensor data to optimize traffic flow [10]. The result is not just reduced congestion and emissions but also a high standard of commuter satisfaction and safety through technology use.

As these cases highlight, while GTC remain a relatively nascent development, substantial inroads through ITS integration are already underway. The success stories lend credence that with careful policy initiatives, technological adoption, and public participation, the theoretical promise of sustainability and efficiency these next-gen corridors hold can translate into tangible, large-scale impact.

While the mathematical framework presented establishes a foundational template for reconfiguring traditional transport corridors into sustainable ecosystems integrated with ITS, certain limitations must be acknowledged along with avenues for future work.

Obtaining high-fidelity multi-modal data at scale remains a challenge. Synthetic data augmentation and simulations can assist while data availability matures.

Linear relationships between variables are assumed for simplicity but real-world behaviors tend to be more complex and nonlinear. Relaxing simplifying assumptions can enhance model accuracy.

The model describes a snapshot of the corridor rather than a dynamically evolving system. Incorporating temporality by adding a time dimension can lend greater realism.

While theoretical validity of the structured methodology is established through the mathematical constructs, quantitatively demonstrating the model’s practical ability to guide transformation through case studies remains to be done.

By acknowledging these limitations and mapping the avenues ahead, this discussion aims to underline significant potential exists to continue refining the approach. Research combining analytics, policy and technology can enrich these early theoretical foundations to drive the sustainable transport vision.

8. Conclusion

The realm of international transport corridors is undergoing a paradigm shift. As global transportation demands rise, coupled with increasingly stringent environmental standards, the necessity for sustainable, efficient, and adaptive solutions becomes paramount.

This paper has explored the significant potential of ITS as a transformative tool to enable the sustainable evolution of international transport corridors. The proposed mathematical modeling provides a structured methodology to understand the dynamics involved in greening traditional corridors. The formulation of the concept of a GTC underscores the paradigm shift needed, where sustainability becomes an integral priority.

The GTC emerges as a holistic ecosystem, where the digital layer, underpinned by ITS, emerges as a linchpin, ensuring operational optimization while upholding stringent environmental goals.

The taxonomy and ecosystem delineated in the paper demonstrate the multifaceted role intelligent systems can play in optimizing corridor operations, right from sensors to analytics to automation. The technological roadmap offers a blueprint for the stepwise integration ITS based of cutting-edge, eco-friendly solutions across infrastructure, systems, construction, energy, and more.

The study highlights the tremendous scope of ITS in enabling a sustainable transportation future, both locally and globally. The synthesis of intelligent systems, environmental ethics and collaborative efforts among nations can bring the vision of truly green, smart, and integrated transport corridors closer to reality.

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