A Simulation-Based Approach to Redesigning a High-Risk Intersection for Improved Sustainability and Traffic Flow

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Abstract: The article addresses issues concerning the improvement of urban transport infrastructure with the aim of enhancing its efficiency and environmental sustainability. It provides a detailed analysis of various approaches within the framework of developing human-centric smart cities and the Environmental, Social, and Governance paradigm. The research highlights that simulation modelling techniques have considerable potential for addressing challenges associated with traffic flow and road infrastructure optimization. To this end, a simulation model of a critical, high-accident-prone interchange in a large city's road network was developed using the Any Logic environment. The model was calibrated and validated using real traffic data collected through video analysis. The conducted experiment tested the hypothesis of converting a problematic signal-free intersection into a roundabout. The results revealed that this reconstruction significantly minimizes conflict points, increases the node's capacity, and reduces the risk of accidents. Furthermore, an assessment confirmed a consequent decrease in vehicular exhaust emissions. The study demonstrates that simulation modelling serves as a vital tool for quantitatively justifying urban planning decisions, allowing for the prediction of their complex impact on a city's transport system. It is concluded that a comprehensive, interdisciplinary approach integrating intelligent technologies and sustainable governance principles is necessary for the positive transformation of urban mobility.

1 INTRODUCTION

The beginning of the 21st century was marked by new trends for the global economy. One trend is associated with growing negative impacts on the environment: increasing urbanization and continuing motorization, despite numerous efforts to curb it. Urbanization processes are accompanied by rising transport demand and motorization of the urban population, creating the need to ensure the sustainability and safety of the transport system.

At the same time, trends in the field of new mobility are associated with the concept of "human-centric" (anthropocentric) systems. A human-centric metropolis is a city that can meet the changing needs of people at any stage of their lives, where its citizens form the core of planning and design. The anthropocentric character of a city is determined by the principles of accessibility, safety, comfort and citizen involvement - everything that makes a city biopositive and sustainable. This falls within the framework of addressing one of the challenges outlined by UNEP "sustainable cities, including planning, transport and green construction".

Given the need to address environmental and social problems in cities, as well as the opportunities for improved management provided by the development of digital technologies, the Environmental, Social, and Governance (ESG) paradigm was developed and is being implemented in many fields. Alongside the principles of the circular economy and the adoption of "green technologies", the ESG paradigm has now demonstrated its effectiveness, particularly for large corporations and large systems. Belonging to the class of large systems, the city's transport network is essential. It underpins both resident mobility and the sustainable operation of the entire urban economy. Consequently, progress towards livable cities hinges on developing this system further, implementing innovations, and applying integrated solutions that foster positive urban transformation.

To achieve these objectives, scientists and businesses are collaborating to develop strategic solutions aimed at transforming current production and consumption systems into a circular economy and adopting green technologies. These measures will help safeguard the environment, improve public health, and ensure general well-being. It is important to note that transitioning to a green economy entails fostering resilient ecosystems, ensuring clean production processes (including logistics and mobility), encouraging healthier consumer choices, and raising environmental awareness among urban populations.

This study introduces a novel simulation-based framework for assessing the multidimensional sustainability impacts of transport infrastructure redesign, integrating traffic performance, safety, and environmental metrics within an ESG-aligned methodology.

2 WAYS TO IMPROVE THE CITY'S TRANSPORT SYSTEM

Considering the trends in the area of new mobility, which will lead to the transformation of the entire transport system, it is crucial to recognize that implementing new mobility models is feasible only within the framework of intelligent transport systems (ITS), which are intricately connected to the concept of "smart city". Only through this integration can a truly human-centered approach to new mobility be achieved. Hence, our analysis focused on identifying the key research directions associated with the concept of "smart city".

Study [1] examines, employing both quantitative and qualitative methodologies, the diverse dimensions of the smart city paradigm encompassing mobility, energy, infrastructure, environment, IoT, data analytics, business operations, urban planning, administrative frameworks, cybersecurity, and socio-cultural dynamics. This paper investigates how advancements in information and communication technologies contribute to enhancing citizens' quality of life, thereby offering novel opportunities for efficient governance of complex urban systems.

Planning and organization of various modes of transport within an intelligent intermodal urban transport system inherently represents a complex and dynamically adaptive task. Intentionally simplifying reality, models assist decision-makers in shaping future transport systems. Meanwhile, Smart City initiatives invest in sensors to observe and manage diverse urban resources, forming part of the Internet of Things (IoT), generating massive volumes of valuable data critical for urban planning and monitoring. In article [2], these newly available IoT-generated datasets are utilized by integrating real-time sensor data directly into contemporary simulation models.

The paper [3] analyzes the successful demonstration of the use of mobile operator geolocation data to better understand the spatial and temporal dynamics of population in a region with diverse settlement patterns. In the paper [4], the authors analyze the key technical challenges and potential benefits of the technologies required to build 6G-enabled smart sustainable cities and their role in improving the quality of life of people and the efficiency of city services. It is envisioned that 6G-enabled SSC will allow seamless connectivity for smart objects such as UAM, IoT sensors, robots, and mobile devices, eliminating constraints on data rates, latency, and coverage.

Mobility has become an increasingly important issue in an era where cities play a pivotal role, housing over 56% of the world's population and producing more than 80% of global GDP. The article [5] offers insights into the scope and emerging trends of smart mobility, going beyond purely technical matters related to ITS, given the rapid pace of technological innovation and diverse urban dynamics.

Over the past few years, a revolution has taken place in the mobility sector, leading to the widespread adoption of lightweight electric vehicles such as e-scooters and e-bikes globally, driven largely by heightened public concern over environmental issues. The article [6] introduces typologies of electric bicycle systems equipped with pedal-assist functionality and demand-driven power management.

One of the most promising areas in the field of mobility is MaaS: Mobility as a Service. The article [7] first discusses the concept of sustainable development set forth until 2030 in relation to urban passenger transport. Then, it examines the role of Information and Communication Technologies in advancing MaaS, presenting a dynamic model of interaction between supply and demand. Finally, the article defines Sustainable MaaS as a key component for ensuring long-term sustainability in urban mobility.

Transforming urban mobility is a complex task given its multi-parameter and multi-dimensional nature. The aim of the paper [8] is to simplify this process by introducing a holistic multi-actor impact analysis framework as a tool for assessing future mobility scenarios, developed within the framework of the SPROUT Horizon 2020 programme.

The transformation of urban mobility, as noted earlier, involves building human-centric systems, meaning the digitalization of transport and management infrastructures aims to create solutions enabling harmonious coexistence between transport and the population. New mobility refers to transportation systems causing minimal environmental impact (low emissions and noise levels) while functioning optimally and securely. To reach these goals, holistic solutions are required, merging the capabilities of ITS with Environmental, Social, and Governance (ESG) principles.

Such smart technologies enable enhanced outcomes through integrated interdisciplinary systems.

Sustainable urban development must be addressed within the context of rapid urbanization and digital community advancement. Article [9] reviews recent IoT innovations enabling sustainable digital communities, including: smart building systems; energy management solutions; sustainable transportation networks; waste recycling technologies. These applications collectively enhance urban resilience by driving eco-efficient development.

The article [10] demonstrates that despite ITS' substantial potential, successful implementation necessitates a holistic interdisciplinary approach. ITS enable sustainable urban development by leveraging cutting-edge technologies and real-time data to: enhance transportation efficiency, safety, and accessibility; reduce traffic congestion; curb fuel consumption and urban pollution. Critical implementation challenges include infrastructure costs, data privacy safeguards, and public acceptance. Collaborative efforts among policymakers, researchers, and transportation planners facilitate effective ITS integration, driving positive urban transformation while improving residents' quality of life and environmental conditions.

The future of sustainable transportation - including effective mitigation of environmental impacts - depends critically on intelligent mobility solutions. Consequently, real-time monitoring of vehicle exhaust emissions and noise pollution is imperative. Authors [11] proposed the NEMO system, incorporating autonomous remote sensing technology to identify and classify high-emission/noise vehicles, pinpoint noise sources in congested traffic and localize explosive gas leaks in real-time.

Smart urban mobility innovations - including ITS, electric/autonomous vehicles, and MaaS - are emerging to enhance urban sustainability by addressing: traffic congestion, urban sprawl, social exclusion and environmental degradation. Study [12] specifically identifies these smart mobility innovations: ITS, alternative fuel technologies, vehicle automation systems, shared mobility platforms, on-demand mobility services and integrated mobility ecosystems.

Connected and Autonomous Vehicles leverage autonomous driving capabilities integrated with communication technologies to function as active components in urban traffic management. As demonstrated in [13], CAVs can execute personalized routing directives and serve as high-precision traffic sensors for transportation authorities. However, critical implementation challenges require addressing cybersecurity vulnerabilities and mitigation of socioeconomic disparities in technology access and mobility options.

Urban streets critically shape sustainable cities through IoT-integrated smart street infrastructure, hybrid grid-radial street network design and safety-enhanced public realms. The article [14] examines this mobility-livability nexus, demonstrating how human-centered street design fosters social interaction and urban comfort. By leveraging synergies between street livability and mobility frameworks - supported by evidence-based safety guidelines - cities can advance Sustainable Development Goal 11's sustainable communities. Outcomes include pedestrian/cyclist-prioritized streetscapes, enhanced public transport accessibility and reduced private vehicle dependency.

Changes to the transport infrastructure have a significant impact on the environmental, social, and governance aspects of the urban transport system. Improved road surfaces and road expansion help reduce traffic congestion, decrease harmful vehicle emissions, and enhance overall mobility comfort.

Thus, changes to road infrastructure have a complex impact on the city's transportation system, affecting environmental, social, and governance aspects. To achieve sustainable development, it is necessary to adopt a holistic approach to solving these issues, considering the interests of all relevant parties involved.

Reconstruction of transport infrastructure inevitably involves financial costs. It's not always possible to find a balance between the benefits of infrastructure improvements and the losses associated with reconstruction costs. For example, article [15] conducts an economic analysis of the construction of bridges, overpasses, and underpasses, taking into account capital expenditures, ongoing and periodic maintenance, and repairs, as well as benefits such as reduced fuel consumption, time savings, and increased traffic.

It has been proven that road infrastructure exerts a long-term positive influence on regional economic development. In [16], a model was developed that incorporates road infrastructure and regional finances as predictors of economic growth. The study utilized structural equation modeling employing Partial Least Squares (PLS) method implemented through WarpPLS version 8.0 software.

Road transport, encompassing a wide range of vehicle types and extensive networks, plays a vital role in economic activity but also creates significant environmental challenges due to its substantial emissions. The authors of the article [17] developed a novel approach to analyzing the relationship between greenhouse gas emissions and road transport in Europe, offering an integrated perspective combining environmental and transport data. The study investigates the link between emissions and transport infrastructure, providing a detailed understanding of how policies and systems affect environmental outcomes. The study utilizes machine learning techniques to enhance the ability to predict future emission trends based on current and historical data.

The paper [18] examines the assessment of the regional impact of road network infrastructure changes in CO_2 equivalents. A detailed assessment of life-cycle CO_2 emissions and the economic costs of road infrastructure construction and maintenance is presented, as well as an assessment of changes in vehicle emissions obtained using a dynamic traffic flow model to estimate changes in vehicle emissions and their infrastructure emissions offsetting potential. In particular, the paper calculates that converting 72 stop signs into roundabouts in El Paso, Texas, reduced daily vehicle CO_2 emissions by more than 50 tons, thus offsetting the CO_2 emissions from construction and maintenance within 2.5-2.9 years.

Over the past decade, simulation modeling methods have been rapidly adopted in studies focused on transport infrastructure resilience. The Any Logic modeling environment is actively used to solve problems related to traffic and road infrastructure modeling.

3 MATERIALS AND METHODS

As evidenced by prior research, studies on enhancing urban transportation system sustainability cover an exceptionally broad spectrum. This scope reflects three fundamental drivers: First, transportation systems serve dual roles in facilitating both freight movement and population mobility, requiring optimization across multiple dimensions-from transport infrastructure and public transit networks to traffic flow management and parking solutions. Second, the imperative to mitigate environmental impacts has spurred diverse management innovations, assessment metrics, and risk management approaches. Third, ongoing technological advancements continue to yield breakthroughs in vehicle design and intelligent traffic control systems.

The creation of complex management systems is important in terms of the transition to a new mobility based on the use of intelligent solutions. In addition, without improving the processes in the transport system, the transition to a human-centric smart city is impossible. The implementation of such systems is possible due to the development of both technical and software tools for solving such problems.

Therefore, this article advances the hypothesis that integrated management systems incorporating diverse sustainability-enhancing proposals can generate synergistic effects capable of improving overall system performance metrics. We examine the application of ESG principles-including potential modifications-to evaluate how such solutions impact final outcomes. Furthermore, the proposed methodology enables validation of performance indicators across related domains. This section details data collection methodologies for performance metric computation, comparative evaluation criteria, and foundational research datasets.

3.1 ESG Principles and Their Adaptive Applications as a Framework for Operational Efficiency Enhancement

The methodological review reveals that developing smart transportation systems through ESG principles and advanced management technologies constitutes a critical factor in urban sustainability. When implemented in compliance with ESG frameworks and through harmonized interventions across these domains, such systems generate synergistic effects while maintaining economic viability. Figure 1 presents the conceptual model of this biopositive urban approach.

The inherent interconnectivity of all system components necessitates that maximum efficiency - both for individual subsystems and the integrated system as a whole - can only be attained through unified pursuit of a shared objective: optimizing sustainability in smart human-centric cities. This synergistic effect emerges through the strategic application of intelligent technologies and centralized governance frameworks.

3.2 The Impact of Infrastructure Changes on Environmental, Social and Management Aspects of the City's Transport System

As evidenced by numerous studies on urban transport systems, sustainability are influenced by multiple factors. One key factor involves infrastructure solutions that fail to accommodate actual traffic flow parameters. This mismatch can increase accident risks, subsequently worsening environmental conditions, exacerbating mobility challenges for the population, and causing logistical disruptions such as delivery delays. Areas with the highest accident frequency are officially designated as "accident-prone zones" in documentation from emergency services and traffic management authorities. Our first case study examines one such location.

The study focused on a section of the street and road network with complex geometry, where traffic density peaks during rush hours, qualifying it as a high-risk accident zone. Figure 2a and b compares the site's layout before and after modifications, while Figure 2c and d displays the 2D simulation model used for analysis under baseline traffic conditions ("before any changes" model).

The interchange configuration, as originally planned during the city's development, was designed based on significantly lower traffic flow parameters compared to current observations, particularly during peak hours.

Since these intersections lack traffic signals and violations frequently occur due to increased congestion-especially at critical junctions highlighted by red circles in Figure 3car crashes became commonplace.

We hypothesized that transforming the existing interchange configuration into a roundabout would represent the most rational solution for this situation. In order to verify our hypothesis, an imitation simulation model was developed in the Any Logic 8 modeling environment.

Traffic characteristics, including flow intensity and density, were determined based on the count of vehicles passing within specific time intervals.

A simulation model "as-is" was subsequently developed, followed by verification and validation procedures. Initially, the accuracy of the model was assessed by ensuring its operational functionality. Thereafter, the model's validity was confirmed by comparing its outputs against actual field data.

Optimization experiments were then conducted to determine optimal traffic parameters, utilizing experimental design methodology. Finally, environmental impact was assessed through vehicle emission measurements.

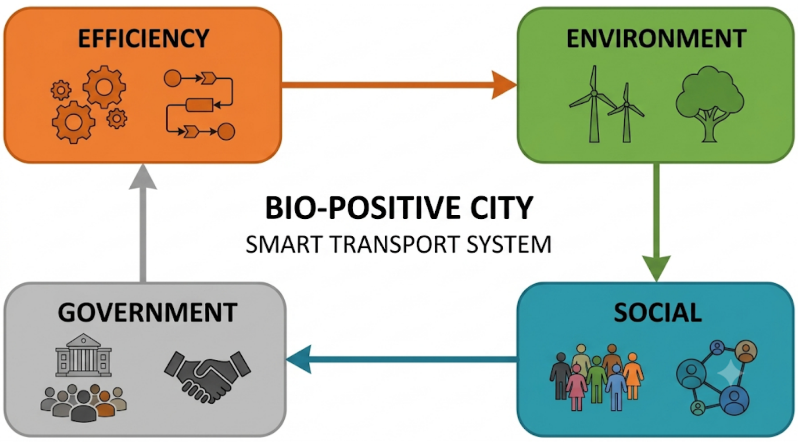


Figure 1: The ESG framework in developing sustainable human-centric cities.

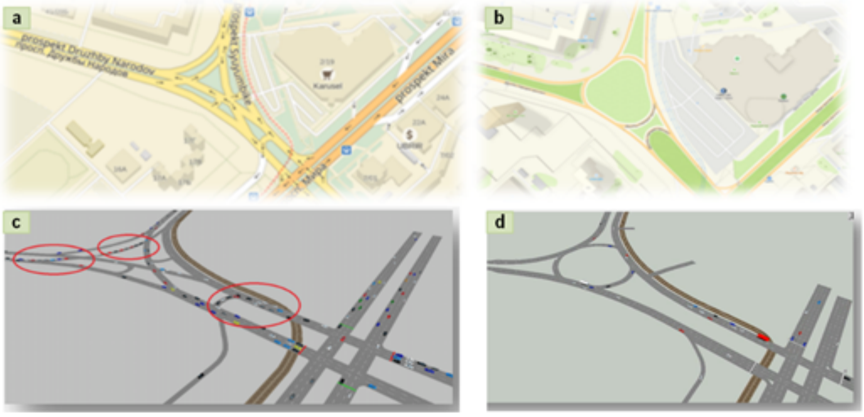
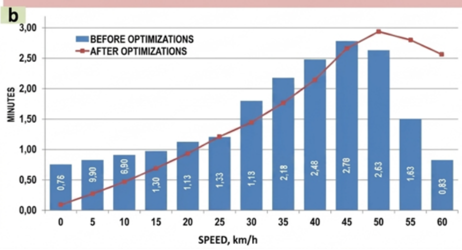


Figure 2: Road network reconfiguration based on simulation modeling study results: a, b - maps before and after reconstruction; c, d - model (before and after reconstruction).

a PARAMETER DESIGNATION	VALUE BEFORE CHANGES	VALUE AFTER CHANGES
Average speed on the road section under study, km/h	35	42
Number of stops per unit of time, pcs.	6	2
Traffic flow density, % of road area	92	67
Average trip duration on the road section, min.	4	1,4



c

SITE CONFIGURATION	EMISSION VOLUMES, T/YEAR			
	CO	NO_X	C_XH_Y	SO_2
BEFORE CHANGES	31.24	2.67	3.92	0.13
AFTER CHANGES	25.42	2.45	3.22	0.11

Figure 3: Comparative data in graphical and tabular form before and after the reconfiguration of the road network interchange.

4 RESULTS AND DISCUSSION

Given unsatisfactory traffic performance at the study site - attributed to its complex geometry and numerous conflict points - the decision was made to reconfigure the road network by implementing a roundabout interchange. A simulation model of the modified road network was developed and tested under existing traffic conditions. The simulation results demonstrated improvements in both traffic flow characteristics and emission reduction.

The graphs and tables in Figure 4 show data on changes in traffic flow parameters and air quality conditions before and after the modifications.

Here, the "pre-modification" data refers to empirical field 1.4 study findings, while the "post-changes" data represents anticipated outcomes derived from simulation models.

Subsequently, the road network configuration in this section was modified in the real-world system according to our recommendations (Fig. 2b). Additionally, this stretch no longer ranks among high-risk accident zones, and traffic performance has notably enhanced,

The indirect effects manifested through improved traffic flow characteristics, which reduced conflict points and decreased both accident frequency and travel time through the section (demonstrating measurable social benefits); the exact number of conflict points before and after reconstruction, and the corresponding node capacity in vehicles per hour, should be reported quantitatively from the AnyLogic simulation output. These modifications additionally yielded environmental improvements

Emission volumes were computed according to traffic flow parameters utilizing formulas incorporating normative emission standards for different vehicle categories.

5 CONCLUSIONS

Transport systems play a crucial role in the socio-economic development of settlements, shaping everyday life, business operations, and territorial appeal. Analysis of the current state and future outlook for improving urban road transport infrastructure underscores the necessity of a comprehensive approach to resolving existing challenges. Low-efficiency road networks impose heightened ecological stress on urbanized areas. Particularly valuable is simulation modelling as an efficient means for refining transport infrastructure solutions.

The scientific contribution of this work lies in the development and validation of a simulation-based methodology for assessing the multidimensional impact of transport infrastructure redesign. Unlike previous studies that focus on isolated aspects, this research introduces a holistic evaluation framework integrating traffic performance, accident risk, and environmental emissions. The novelty is demonstrated through: (1) the use of real-world traffic data for model calibration and validation, ensuring the reliability of predictions; (2) the quantification of synergistic effects from converting an uncontrolled intersection into a roundabout, including improved capacity, reduced conflict points, and lower emissions; and (3) the alignment of infrastructure solutions with ESG principles, providing a replicable approach for sustainable urban transport planning.

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