Enhancing Urban Mobility: Traffic Signal Parameter Optimization via Simulation Modeling

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Abstract: This article investigates methods for optimizing traffic light control parameters with the aim of improving urban traffic efficiency. Modern approaches to ensuring the sustainability of urban transport systems are discussed. The study concludes that simulation modelling serves as a leading methodology for analysing transportation systems and identifying optimal solutions to diverse challenges, which ultimately enhances traffic flow characteristics and increases the resilience of the transport network. A simulation model of a major city intersection has been developed, an optimization experiment carried out, and optimal values for traffic light signal phases have been determined. The model was parameterized using real traffic flow data collected through video observations during morning peak hours. An optimization experiment was conducted with traffic light phase durations as variable inputs, aiming to minimize total vehicle travel time through the intersection. The results demonstrated significant improvements: a reduction in crossing times of 11.71% for passenger cars, 16.93% for buses, and 17.68% for trucks. These optimizations translate into direct benefits such as reduced fuel consumption from idling and substantial indirect co-benefits, including social gains from shorter travel times, enhanced road safety, and a positive environmental impact through lowered vehicular emissions. The research underscores the efficacy of integrating simulation-based Decision Support Systems into urban traffic management for developing adaptive, sustainable, and human-centric transport networks.

1 INTRODUCTION

In today's world, the rapid increase in the number of vehicles and the intense usage of urban roads lead to several issues that significantly affect both residents' daily life and the city's economy. Key among these are traffic congestion, extended travel times, higher accident risks, and harmful environmental consequences.

Ensuring a high level of accessibility, safety, and environmental sustainability in urban transportation systems is emerging as a critical factor for sustainable community development. Addressing this challenge requires ongoing efforts to continuously refine current approaches to traffic organization.

Traffic light efficiency plays a crucial role in maintaining uninterrupted traffic flows and minimizing street congestion. Optimizing traffic light parameters significantly affects road capacity, reduces average vehicle delay times, and alleviates overall traffic load across the transportation network.

The importance of optimizing traffic light control parameters stems from the continuous growth in vehicular traffic volumes and the high utilization rates of urban roads. The performance of traffic signals directly influences street throughput, average waiting times at intersections, and total vehicle journey duration.

Although there exist many approaches to traffic management, traditional methods for calculating traffic light cycle timings and phases frequently fall short when addressing the needs of heavy urban traffic. Consequently, developing optimization techniques capable of rapidly and effectively adjusting traffic lights becomes particularly important.

This research aims to investigate and develop a scientifically grounded method for determining optimal traffic light control parameters. By doing so, it seeks to achieve substantial reductions in vehicle delays, ensure balanced distribution of traffic flows, and minimize negative outcomes resulting from inefficient traffic light signaling.

2 TRENDS IN SUSTAINABLE URBAN TRANSPORT

Numerous scientific studies develop and enhance solutions addressing urban sustainability, categorizable in various ways based on their object of study. Accordingly, a key research focus has been the assessment of urban sustainability. Given that cities constitute complex systems of interdependent subsystems, the development paradigm for each must be fundamentally aligned, prioritizing the achievement of system-wide sustainability.

The authors [1] note that currently, despite urban transport's significant role in addressing socio-environmental challenges, no universally established criteria exist for assessing its sustainability. According to them, particular emphasis must be placed on examining the criteria, their interrelationships, and identifying trade-offs. Drawing on a synthesis of relevant literature, the authors highlighted the importance of human factors and theoretical frameworks such as innovation diffusion and (Multi-Level Perspective) MLP in understanding large-scale transport transitions.

To refine planning and boost the sustainability of urban transport systems, authors [2] argue that establishing and systematizing a sustainability assessment framework is essential. For instance, given that public transport ranks among the most sustainable modes, prioritizing its use alongside cycling, walking, and personal mobility devices will enhance environmental sustainability.

The authors [3] identify four innovation clusters in transportation that enable a comprehensive system assessment.

1) The 'New Mobility' cluster focuses on human daily activity patterns.
2) The 'Urban Logistics' cluster examines goods movement operations.
3) The 'Intelligent System Management' cluster analyzes infrastructure-agency interoperability.
4) The 'Societal Integration' cluster addresses community-transport system interfaces.

The review [4] demonstrates that sustainability research encompasses: transportation planning and policy development; environmental impact variables; demand and traffic flow management; energy and propulsion technologies; non-spatial interventions. Consequently, the author contends that future research should develop optimization models integrating social transportation dimensions with environmental impact mitigation. The analysis further identifies critical sustainability dimensions (economic, environmental, social), characterizes objective functions, incorporates stakeholder considerations in modeling, and examines network-level implementations.

As primary pollution sources, cities must develop and deploy effective mitigation instruments. Review [5] examines diverse approaches in transport-oriented land-use planning, including mixed-use zoning and compact city design, to accelerate the transition toward zero-emission mobility and reduce private vehicle dependency. The authors contend that integrating artificial intelligence into transport modeling and MaaS frameworks represents pivotal innovations for strategic land-use planning.

As cities constitute primary pollution sources, developing and implementing effective mitigation instruments becomes imperative. Review [6] examines diverse approaches in transport-oriented land-use planning, including mixed-use zoning and compact city design, which can accelerate the transition to zero-emission mobility and reduce private vehicle dependency. The authors contend that integrating artificial intelligence into transport modeling and ‘Mobility as a Service’ frameworks represents pivotal innovations for strategic land-use planning.

Multimodal integration (combining cycling with fixed-route public transport) represents another key strategy for enhancing transport sustainability by providing tailored mobility services. Study [7] employs a combinatorial accessibility assessment methodology, evaluating horizontal (geographic) and vertical (socioeconomic) equity dimensions across four development scenarios: (a) Baseline fixed-route transit, (b) Baseline transit + new metro line, (c) Baseline transit + new bicycle network, (d) New metro line + new bicycle network. Results demonstrate that balanced multimodal configurations deliver optimal equity outcomes, necessitating integrated transportation-land use planning to achieve mobility justice.

The findings of the study [8] suggest that the digital economy exerts a nonlinear influence on green development and indirectly shapes urban greening processes through nonlinear mediation effects of green technologies. The authors highlight significant heterogeneity effects, observed both between urban agglomerations and individual cities, as well as between resource-dependent and non-resource-dependent cities.

Given the importance of enhancing sustainable urban mobility management, the study authors [9] established Sustainable Urban Mobility Indicators, identifying which are most and least appropriate in specific contexts. Their analysis reveals the highest-priority indicators as: road congestion levels, public transport accessibility for low-income populations, energy efficiency, equitable access to mobility services, and multimodal integration. This approach enables a holistic framework for implementing sustainable mobility strategies at the urban level.

The establishment of urban ecosystems seeks to introduce rational management across all sectors of city activities, including logistical and transportation improvements. These measures are intended to enhance urban resilience and elevate cities to a new, human-centric standard. Several studies conducted in this domain are summarized in this section.

Numerous studies investigate how implementing Environmental, Social, and Governance (ESG) principles enhances efficiency and sustainability in transportation and logistics.

Ensuring the Internet of Vehicles (IoV) sustainability necessitates multi-perspective solutions, particularly within ESG frameworks. The review [10] systematically analyzes each dimension of IoV research through this tripartite lens. A key contribution is a conceptual IoV model mapping interconnected ESG dimensions to enable multi-tiered system sustainability.

A growing body of research examines linkages between ESG adoption and corporate performance. Study [11] employs Data Envelopment Analysis (DEA) to benchmark operational efficiency in transportation firms and OLS regression to analyze relationships between composite ESG scores and financial outcomes. Phase 1 applied DEA to assess business performance across US and Chinese transportation enterprises. Regression results indicate only environmental and social dimensions demonstrate statistically significant positive impacts on corporate performance.

The study [12] investigates big data's influence on corporate ESG performance. The authors demonstrate more pronounced effects among firms: in low-pollution industries; with limited digital maturity; not undergoing rigorous audits. Facing external regulatory pressures, companies proactively enhance ESG metrics to mitigate reputational risks. Consequently, big data will significantly shape both the quality and strategic direction of corporate green innovation, critically advancing ESG performance and sustainable enterprise development.

The study [13] employs a Spatial Durbin Model to empirically analyze ESG ratings' impact on carbon emissions. It quantifies both direct and indirect effects, identifies spatial spillover effects, and examines regional heterogeneity and city-size dependencies. Results confirm ESG ratings exert a significant carbon mitigation effect with measurable spatial diffusion.

The ESG assessment framework enables forecasting of growth prerequisites in the transportation sector. Amid China's national 'carbon peak' and 'carbon neutrality' strategies, international trade port operators increasingly prioritize ESG metrics. Study [14] selected eight sector benchmark firms, revealing that high-performing operational units demonstrate superior port efficiency. Crucially, ESG evaluation extends beyond financial returns to encompass corporate environmental, social, and governance externalities.

As authors note [15], the significance of sustainable development and ESG is growing in the context of achieving the Sustainable Development Goals by 2030. The lack of high-precision ESG data creates challenges in ESG reporting evaluation, which can be addressed through implementing Industry 4.0 technologies. These solutions would enable real-time data transmission, data authentication, forecasting, as well as enhanced transparency and data structuring. Furthermore, blockchain technology implementation would facilitate tracking of organizational sustainability efforts.

The diversified application of the Industry 4.0 doctrine and the digitalization of socio-economic systems reveals problems in the design, control and evaluation of efficiency in smart city logistics. The article [16] provides a literature review on the topic and digitalization of urban logistics, taking into account the prospects and limitations of ESG. From the authors' point of view, the theoretical foundations for the creation and development of intelligent systems for the digitalization of smart city logistics, taking into account the ESG paradigm, are based on the Industry 4.0 doctrine and are promising for future research.

Traditional traffic signal systems based on static or semi-fixed timers are unable to adapt to dynamic traffic conditions, which exacerbates congestion and limits inclusiveness. To address these limitations, this paper [17] proposes H-ATLM (Hybrid Adaptive Traffic Signal Management), a system that uses a deep deterministic policy gradient (DDPG)-based reinforcement learning algorithm to dynamically optimize traffic signal timing based on real-time data. The system integrates advanced sensor technologies, such as cameras and induction loops, to monitor traffic conditions and adaptively adjust signal phases.

In [18], an adaptive traffic light controller based on fuzzy logic for optimizing traffic flow at an isolated intersection is introduced. A set of fuzzy rules was developed that, utilizing information gathered from road sensors (queue length, arrival and departure flows), computes the amount of time by which the subsequent phase should be reduced or prolonged. The proposed fuzzy control system comprises two components: one for the primary passage (handling a high volume of vehicles) and another for the secondary passage (serving fewer vehicles). The suggested controller is benchmarked against a conventional fixed-timing traffic light scheme in three distinct traffic-demand scenarios, thus validating the efficacy of the devised decision-making rules.

To prevent issues related to waiting for traffic lights by emergency vehicles, a study [19] suggests developing a system based on Internet-of-Things sensors that would identify the arrival of emergency vehicles in problematic zones by detecting their transmitted signals. Such an RFID-based Intelligent Transportation Management System could substantially enhance the well-being of road users, economic benefits, and environmental sustainability. Employing a minimum-distance trigger mechanism, a dynamic navigation system combined with smart traffic lights assess the movement patterns of emergency vehicles.

3 MATERIALS AND METHODS

In our view, the most effective management approach could be a Decision Support System (DSS) whose computational core would comprise a suite of simulation models. Operating within a unified framework, these models would utilize a shared repository of input data on the functioning of all urban systems. This data would be continuously updated through the monitoring of various parameters. Running experiments with these models would then provide reliable information on subsystem performance under changing conditions, enabling the identification of optimal adjustments for various city subsystems. Consequently, decisions could be made more operationally, potential risks assessed, and the negative impacts of suboptimal decisions or unforeseen events mitigated.

The conceptual diagram of the DSS will appear as shown in Figure 1 Since the DSS aims to increase the efficiency of unified transport system management during the transition to new mobility, each module has specific intermediate objectives with corresponding implementation algorithms.

Since decision-making adequacy relies heavily on information quality, the primary objective of the “data collection and initialization” module is to define how the collected information will be utilized before transferring it to the database for storage and further processing. To achieve this, we categorized the information into three distinct groups based on their frequency of modification and application. The first group consists of conditionally constant information that only changes very rarely as a result of large-scale projects. This type of data is useful for strategic planning, helping verify the effectiveness of various decisions. It typically includes infrastructure-related data, regulatory documentation, calculation methodologies, etc. The second group involves data that changes more frequently and is applied in tactical planning efforts. This data helps define the means for achieving strategic goals over a medium-term horizon. As these datasets are prone to changes, we account for probable alterations and make adjustments accordingly. Finally, the third group comprises operationally managed data, which experiences continuous changes based on ongoing events and situational dynamics. Feedback-driven adjustments ensure this data remains current. One common illustration of this type could be intelligent traffic management systems, such as adaptive traffic signals responding to actual traffic flows.

Accordingly, the means of obtaining information and its preliminary processing vary. Information may originate either from smart infrastructure sensors (such as cameras, smart traffic lights, and smart vehicles), or from external sources (including government authorities providing regulatory documents, infrastructure project developers, and strategic planning agencies).

Data belonging to the first group are embedded into processing algorithms and models as static input parameters, with updates implemented whenever relevant changes arise.

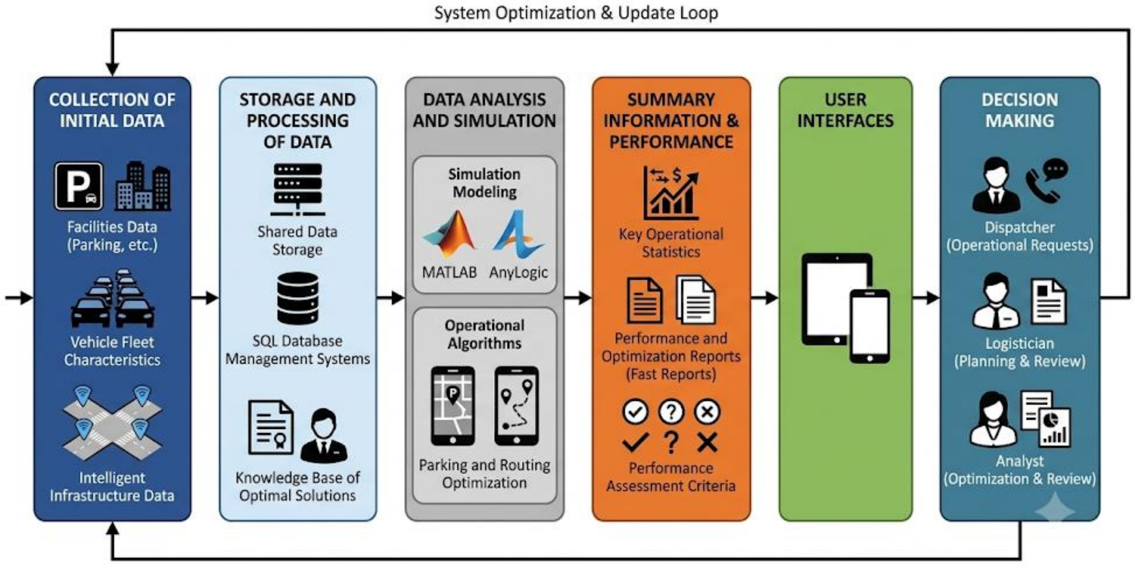

Figure 1: Conceptual diagram of the decision support system.

Consequently, any models or applications being developed should allow for this feature, especially when refreshing foundational data sets. Second-group data, given their greater volatility, require regular updates following predetermined schedules, e.g., monthly, quarterly, or annually. Meanwhile, operational-level data streams are continuously fed into the central control unit in real-time, enabling ongoing refinements to management models and generation of statistical reports.

To ensure the reliability of the simulation model, calibration and validation procedures were performed. The model was calibrated using traffic flow data collected during morning peak hours. Calibration involved adjusting vehicle speed distributions, acceleration/deceleration profiles, and driver behavior parameters to match observed field conditions.

Validation was performed by comparing simulated and observed queue lengths at the intersection approach during the same time period. The mean absolute percentage error between simulated and observed queue lengths was 8.3%, indicating satisfactory model accuracy.

As the simulation incorporates stochastic elements (vehicle arrival distributions, driver behavior variability), each optimization scenario was replicated 10 times with different random seeds. The coefficient of variation for total travel time across replications was below 5%, demonstrating stability of the optimization results.

4 RESULTS AND DISCUSSION

Numerous studies of urban transportation systems demonstrate that safety and sustainability rely heavily on multiple interconnected factors. Among them, one pivotal aspect concerns traffic signals at intersections that do not consider real-time traffic flow dynamics. Such discrepancy may heighten the likelihood of accidents, thereby further deteriorating environmental quality and intensifying mobility challenges within cities.

Taking one of the congested sections of the street and road network in Naberezhnye Chelny as an example, we utilize the simulation model developed in AnyLogic 8 software to determine optimal traffic light phase cycle durations considering traffic intensity.

To gather primary data, field observations of traffic flows were conducted. The traffic volume count was performed on Friday (a weekday) during the morning peak hour from 7:00 to 7:55. Four vantage points equipped with video cameras captured the traffic flow parameters in every direction.

Traffic volume data were aggregated into 10-minute intervals to capture peak-hour dynamics while smoothing short-term fluctuations. This interval length was selected as a compromise between capturing temporal variability and ensuring sufficient vehicle counts for statistical reliability.

Vehicle counts were converted to passenger car equivalent units using standard conversion factors based on the Highway Capacity Manual: 1.0 for passenger cars, 1.5 for trucks, and 2.0 for buses.

All turning movements at the intersection were included in the analysis (straight-through, right-turn, and left-turn movements).

The traffic intensity for the studied section, based on the collected data, is shown in Table 1. Here, the section number corresponds to the survey point number in Figure 2, which also indicates vehicle approach directions.

In developing the model, the following agent types were implemented: "Road Network" (defining the roadway infrastructure), "Car", "Truck", and "Bus" (representing respective vehicle classes), "Traffic Light" (modeling signalized intersection control). Following agent specification, a traffic flow diagram was created to assign agents to specific road segments with defined intensity parameters.

Figure 3 presents the process flow diagram of the simulation model (aligned with the movement directions).

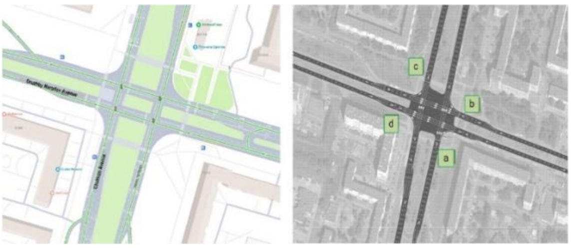

Figure 2: Map of the intersection under study dentification numbers of traffic directions.

To determine optimal values of the input parameters, an optimization experiment was conducted using the built-in OptQuest optimizer. Signal phase durations were selected as the variable parameters. The objective function in the optimization experiment was to minimize the total travel time of vehicles passing through the intersection. Figure 4 displays the pre-optimization travel times for all vehicle types compared to post-optimization results for passenger cars on this roadway segment.

The optimization experiment revealed that traffic signal phase optimization could reduce: vehicle traversal times by 11.71% for passenger cars, bus transit times by 16.93%, truck transit times by 17.68%.

The indirect benefits include fuel savings from reduced vehicle idling, social improvements through shorter travel times for both public transport passengers and private vehicle users, and enhanced road safety due to optimized traffic flow parameters. Additionally, these measures yield positive environmental impacts through reduced vehicular emissions (Fig. 5).

Emissions were estimated using the following methodology: fuel consumption at idle: 0.6 L/h for passenger cars, 1.2 L/h for trucks, and 1.5 L/h for buses [20]; emission factors per liter of gasoline consumed [21]: CO_2: 2.32 kg/L, CO: 0.15 kg/L, NO_x: 0.02 kg/L, HC: 0.01 kg/L.

5 CONCLUSIONS

This study demonstrated that simulation-based optimization of traffic signal parameters can serve as an effective tool for improving the operational efficiency and sustainability of urban transport systems. Using a calibrated and validated AnyLogic model of a congested signalized intersection, the research showed that traffic light phase optimization can significantly reduce vehicle crossing times under real peak-hour conditions. The reliability of the simulation results was supported by validation against observed queue lengths, which produced a mean absolute percentage error of 8.3%, while repeated optimization runs confirmed the stability of the obtained solutions.

Table 1: Traffic counts for selected 10-minute observation intervals during the morning peak period.

Time interval	Segment ID	Straight-through traffic count (veh/h)			
		Light vehicles	Trucks	Buses	Total
7:00-7:10	1	642	0	126	768
7:15-7:25	2	198	6	18	222
7:30-7:40	3	1536	12	60	1608
7:45-7:55	4	714	12	24	750

Time interval	Segment ID	Right-turn traffic count (veh/h)			
		Light vehicles	Trucks	Buses	Total
7:00-7:10	1	246	0	36	282
7:15-7:25	2	198	0	24	222
7:30-7:40	3	234	0	12	246
7:45-7:55	4	348	0	0	348

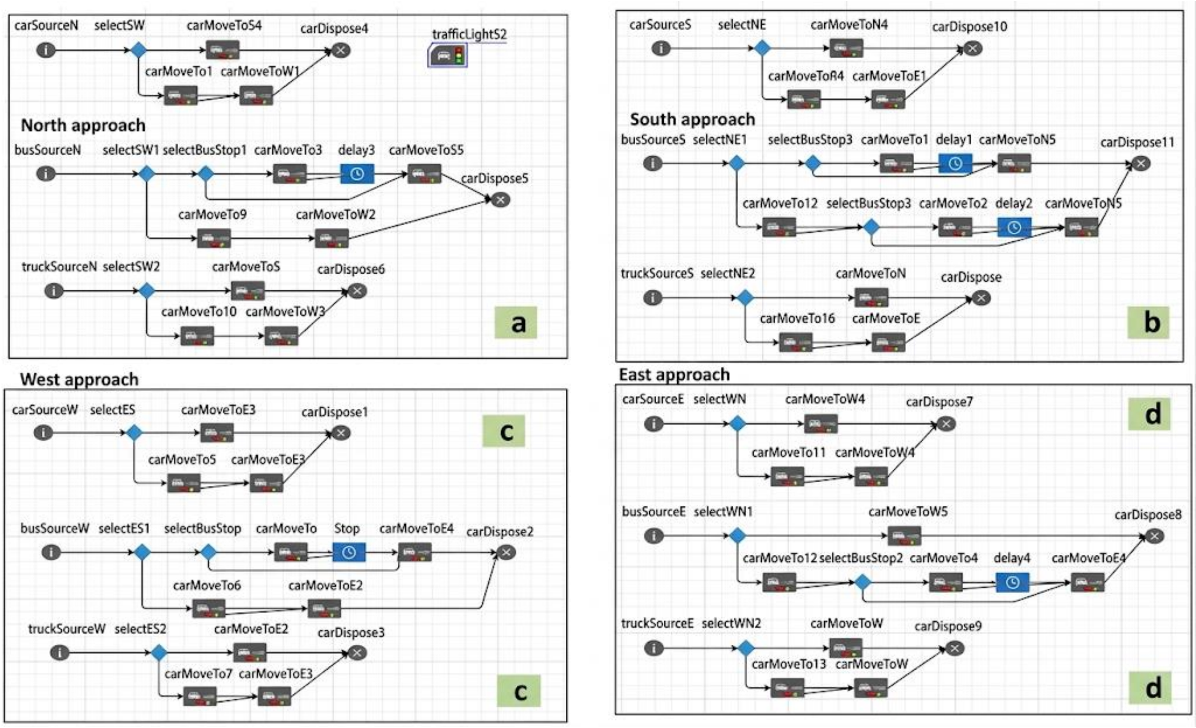

Figure 3: Structural diagram of the model.

Name	Mode (phase duration), sec.					
	Before optimization			After optimization		
	Green	Yellow	Red	Green	Yellow	Red
Chulman Avenue	42	3	45	23	3	64
Druzhby Narodov Avenue	36	3	51	26	3	61

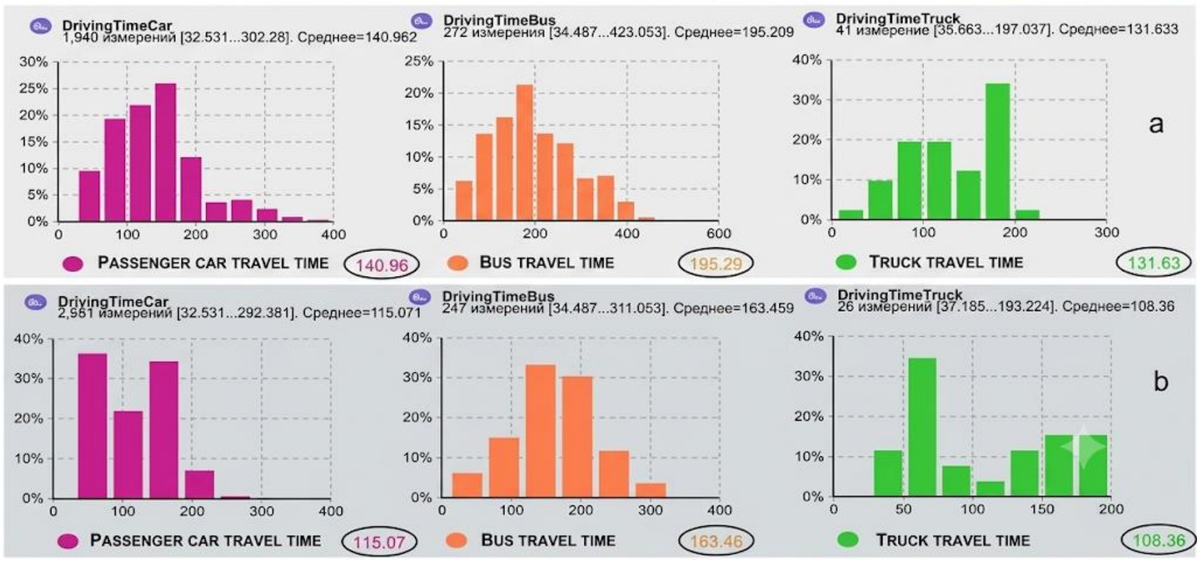

Figure 4: Intersection crossing time: a) before optimization and b) after optimization.

a

Vehicle type	Specific emission, g/kg				
	CO	VCO	NO_x	SO_2	CO_2
Passenger cars	21,5	2,4	5,8	0,54	3120
Trucks and buses with a gross weight of up to 3500 kg	21,5	2,4	5,8	0,54	3120
Trucks and buses with a gross weight over 3500 kg	360,0	39,0	30,0	0,54	2500

b

Name of the pollutant	Emission volumes	
	Before optimization	After optimization
Carbon monoxide (CO), g	190 802.2	190 588.3
VOC hydrocarbons (in terms of of CH1.85), g	20 705.66	20 682.46
Nitrogen oxides NO_X (in terms of NO_2), g	17 904.89	17 884.83
Sulfur dioxide (SO_2), g	540,15	539,54
Carbon dioxide CO_2, g	2 810 768.25	2 807 618.41

Figure 5: Environmental impact of traffic light optimization: a) emissions from burning 1 liter of gasoline, b) total emissions based on the estimated number of passing vehicles.

The optimization experiment revealed measurable performance gains for all major vehicle categories. After adjusting signal phase durations, the average crossing time decreased by 11.71% for passenger cars, 16.93% for buses, and 17.68% for trucks. These results confirm that even localized intersection-level interventions can generate substantial operational benefits, especially in urban areas characterized by heterogeneous traffic composition and high peak-hour demand. The findings therefore support the practical value of simulation modeling as a decision-support instrument for traffic management authorities seeking to improve intersection performance without immediate large-scale infrastructure expansion.

Beyond traffic efficiency, the study also highlights the broader sustainability implications of signal optimization. Reduced delays and shorter idling periods contribute not only to lower fuel consumption, but also to decreased transport-related emissions, improved travel conditions for public transport, and potential safety gains due to smoother and more balanced traffic flows. In this sense, traffic signal optimization should be viewed not merely as a local control problem, but as part of a wider strategy for building more adaptive, environmentally responsible, and human-centered urban mobility systems.

An important contribution of the study is the integration of the optimization task into the concept of a broader decision support system. The proposed approach demonstrates how traffic management can be embedded within a modular digital framework that combines data collection, simulation, evaluation, and control logic. Such an architecture creates opportunities for more responsive and evidence-based transport planning, including future integration with smart infrastructure, real-time monitoring systems, and other components of intelligent urban mobility management.

At the same time, the study has several limitations. The model was developed for one intersection, using observations collected during the morning peak period of a weekday, which limits the direct generalization of the results to other temporal conditions, traffic patterns, and network configurations. Future research should therefore extend the analysis to multiple intersections, longer observation periods, multimodal traffic scenarios, and adaptive real-time control strategies. It would also be beneficial to incorporate network-wide coordination effects and more detailed environmental and safety indicators. Overall, the study confirms that simulation-based traffic signal optimization provides a practical and scalable foundation for enhancing urban mobility efficiency and sustainability.

REFERENCES

[1] L. Kraus and H. Proff, "Sustainable Urban Transportation Criteria and Measurement-A Systematic Literature Review," Sustainability, vol. 13, no. 13, 2021, [Online]. Available: https://www.mdpi.com/2071-1050/13/13/7113.

[2] L. Persia, E. Cipriani, V. Sgarra, and E. Meta, "Strategies and Measures for Sustainable Urban Transport Systems," Transp. Res. Procedia, vol. 14, pp. 955-964, May 2016.

[3] T. Goldman and R. Gorham, "Sustainable Urban Transport: Four Innovative Directions," Technol. Soc., vol. 28, pp. 261-273, Oct. 2005.

[4] T. Borchers, D. Wittowsky, and R. A. Souza Fernandes, "A Comprehensive Survey and Future Directions on Optimising Sustainable Urban Mobility," IEEE Access, vol. 12, pp. 63023-63048, Apr. 2024.

[5] T. Deweerdt and A. Fabre, "The Role of Land Use Planning in Urban Transport to Mitigate Climate Change: A Literature Review," Adv. Environ. Eng. Res., vol. 3, 2022, [Online]. Available: https://www.researchgate.net/publication/362948043, [Accessed: Jan. 15, 2026].

[6] A. Addas, "Role of Urban Planning Standards in Improving Lifestyle in a Sustainable System," Sustainability, vol. 15, no. 12, 2023, [Online]. Available: https://www.mdpi.com/2071-1050/15/12/9171, [Accessed: Jan. 15, 2026].

[7] S. Tsigdinos, P. Tzouras, I. Kosmidis, E. Bakogiannis, and K. Kepaptsoglou, “Examining the Impact of Bicycle-Oriented Multimodality on Accessibility and Transport Equity in the Metropolitan Area of Athens, Greece,” Int. J. Urban Sci., vol. 28, 2024, [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/12265934.2024.2317174, [Accessed: Jan. 15, 2026].

[8] X. Li, S. Li, Q. Wu, and J. Cheng, “Influence Mechanism of Digital Economy on Urban Green Development Efficiency: A Perspective on New Quality Productive Forces,” Sustainability, vol. 17, 2025, [Online]. Available: https://www.mdpi.com/2071-1050/17/10/4539, [Accessed: Jan. 15, 2026].

[9] I. Chatziioannou et al., “Ranking Sustainable Urban Mobility Indicators and Their Matching Transport Policies to Support Liveable City Futures: A MICMAC Approach,” Transp. Res. Interdiscip. Perspect., vol. 18, 2023, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2590198223000350, [Accessed: Jan. 15, 2026].

[10] M. Kostrzewski, M. Marczewska, and L. Uden, “The Internet of Vehicles and Sustainability-Reflections on Environmental, Social, and Corporate Governance,” Energies, vol. 16, no. 7, 2023, [Online]. Available: https://www.mdpi.com/1996-1073/16/7/3208, [Accessed: Jan. 15, 2026].

[11] G. T. N. Pham, P. P. Tran, M.-H. Le, H. N. Vo, C. D. Pham, and H.-D. Nguyen, “The Effects of ESG Combined Score on Business Performance of Enterprises in the Transportation Industry,” Sustainability, vol. 14, no. 14, p. 8354, Jul. 2022, [Online]. Available: https://www.mdpi.com/2071-1050/14/14/8354, [Accessed: Feb. 18, 2026].

[12] M. Wang and D. Zhang, “Big Data Infrastructure and Corporate ESG Performance: Evidence from Listed Chinese Manufacturing Companies,” Sustainability, vol. 16, no. 12, 2024, [Online]. Available: https://www.mdpi.com/2071-1050/16/12/5147, [Accessed: Jan. 15, 2026].

[13] W. Yang and Y. Hei, “Research on the Impact of Enterprise ESG Ratings on Carbon Emissions from a Spatial Perspective,” Sustainability, vol. 16, no. 9, 2024, [Online]. Available: https://www.mdpi.com/2071-1050/16/9/3826, [Accessed: Jan. 15, 2026].

[14] Y. Zhang, Z. Xin, and G. Gan, “Evaluating the Sustainable Development Performance of China’s International Commercial Ports Based on Environmental, Social and Governance Elements,” Sustainability, vol. 16, no. 10, 2024, [Online]. Available: https://www.mdpi.com/2071-1050/16/10/3968, [Accessed: Jan. 15, 2026].

[15] A. Saxena et al., “Technologies Empowered Environmental, Social, and Governance (ESG): An Industry 4.0 Landscape,” Sustainability, vol. 15, no. 1, 2023, [Online]. Available: https://www.mdpi.com/2071-1050/15/1/309, [Accessed: Jan. 15, 2026].

[16] S. Barykin et al., “Smart City Logistics on the Basis of Digital Tools for ESG Goals Achievement,” Sustainability, vol. 15, no. 6, 2023, [Online]. Available: https://www.mdpi.com/2071-1050/15/6/5507, [Accessed: Jan. 15, 2026].

[17] M. Almaliki et al., “Adaptive Traffic Light Management for Mobility and Accessibility in Smart Cities,” Sustainability, vol. 17, no. 14, 2025, [Online]. Available: https://www.mdpi.com/2071-1050/17/14/6462, [Accessed: Jan. 15, 2026].

[18] A. Vogel, I. Oremović, R. Šimić, and E. Ivanjko, “Improving Traffic Light Control by Means of Fuzzy Logic,” in Proc. 2018 Int. Symp. ELMAR, Zadar, Croatia, Nov. 2018, pp. 51-56.

[19] M. Ahmad, U. Musa, Y. Ohiani, and M. Abimbola, “Faults and Solutions for Smart Traffic Lights,” Middle East Res. J. Eng. Technol., vol. 4, no. 1, pp. 1-4, 2024, [Online]. Available: https://kspublisher.com/media/articles/MERJET_41_1-4.pdf, [Accessed: Jan. 15, 2026].

[20] U.S. Environmental Protection Agency (EPA), Idle Vehicle Emissions: Basics and Impacts, EPA-420-F-20-015, Office of Transportation and Air Quality, Washington, DC, USA, 2020, [Online]. Available: https://www.epa.gov, [Accessed: Jan. 15, 2026].

[21] European Environment Agency (EEA), EMEP/EEA Air Pollutant Emission Inventory Guidebook 2019, EEA Report No. 13/2019, Luxembourg: Publications Office of the European Union, 2019, [Online]. Available: https://www.eea.europa.eu, [Accessed: Jan. 15, 2026].