Smart Parking Solutions for Sustainable Cities: A Simulation Modeling Framework

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Abstract: This article explores the potential for addressing issues related to improving the sustainability and safety of a city's transportation system. The study demonstrates the need for a comprehensive approach that considers not only the direct but also the indirect effects of potential solutions, selecting those that enhance the overall sustainability and safety of the system. The article presents a conceptual model of such a system and illustrates implementation methods using a large city as an example. Furthermore, it demonstrates how simulation modelling can address urban transportation network issues and quantifies the impact of implementing the proposed solutions. As a specific case, the research focuses on optimizing parking management-a critical factor in urban mobility. A simulation-based Decision Support System is proposed, with a microsimulation model developed in AnyLogic for the parking area of a children's educational center. By comparing the baseline ("as-is") situation with a managed ("to-be") system featuring priority reservations, the study quantifies key improvements. The results show an 85% reduction in average parking search time for teachers and a 62% reduction for visitors during peak hours. Furthermore, the optimized system achieves a 65.9% decrease in associated CO_2 emissions. These findings validate the model's effectiveness and highlight the significant environmental and social co-benefits of intelligent parking management within a broader "smart city" framework, contributing to reduced congestion and enhanced urban liveability.

1 INTRODUCTION

Transportation plays a key role in supporting the functioning of modern cities, facilitating economic development, social mobility, and environmental sustainability. However, modern transportation systems face several serious challenges stemming from urban population growth, rising traffic intensity, changing climatic conditions, and aging infrastructure. These challenges pose risks of accidents, complicate maintaining normal functioning of transportation systems, and lower the quality of provided transportation services.

Typically, modifications to transport infrastructure can result in substantial improvements to the transport system's condition. Nonetheless, ideally, organizational measures targeting the enhancement of the city's transport system, especially through decarbonization efforts, should be pursued. Such outcomes can only be realized via integrated approaches, including redesigning vehicles to boost their energy efficiency and environmental performance, updating urban transport governance mechanisms (such as introducing smart transport systems and advanced infrastructure). Additionally, it is essential to tackle social challenges, such as improving eco-awareness among citizens, discouraging unnecessary travel, advocating for non-motorized forms of transport, and shifting toward greener transportation options like electric and autonomous vehicles while phasing out conventional diesel and petrol-fueled cars in favor of alternative fuels and hybrid technologies. Consequently, addressing transport-related issues effectively necessitates relying on an evaluation framework incorporating both primary and ancillary effects to minimize detrimental impacts on the environment and societal well-being.

In our study, we examined the current challenges regarding the transition to an anthropocentric smart city, identifying key pathways. This review is presented in Section 2, which analyzes trends in sustainable development of urban transport systems. The third section, "Materials and Methods," describes the methodological approach to enhancing the sustainability of the city's transport system through the creation of a decision support system. The computational core of this system is a model designed to analyze and improve its performance. Section 4 provides illustrative examples of solutions to a specific problem, while Section 5 summarizes the findings of the study, identifies its limitations, and outlines directions for future research.

2 TRENDS IN SUSTAINABLE URBAN TRANSPORT

One of the most widespread approaches to creating livable cities has been Transit-Oriented Development (TOD), emphasizing the creation of districts with convenient access to public transportation, thus encouraging car-independent living patterns. Study [1] investigates the link between proximity to public transport stops and daily routines of residents in Auckland, New Zealand-a car-reliant city striving to adopt a sustainable TOD model. Given evolving transportation capabilities and technological innovations like electric vehicles alongside other behavioral influencers, it is essential to reconceptualize the traditional half-mile radius or 15-minute walk as the sole metric for measuring accessibility.

The aim of the paper [2] is to analyze and evaluate the problems of growing traffic congestion, increased emissions, and enhanced road safety using Artificial Intelligence (AI) and the Internet of Things (IoT) implemented in Polish cities to improve traffic management. The study employs a mixed methodology, combining crowd-sourced mobility data analysis (from GPS, smartphones, and municipal reports), GIS tools for congestion mapping, big data analytics, and machine-learning algorithms to assess trends and forecast traffic scenarios across seven major Polish cities: Warsaw, Kraków, Wrocław, Gdańsk, Poznań, Katowice, and Łódź. These cities have already introduced dynamic traffic lights, intelligent pedestrian crossings, accident-prediction systems, and parking-space management solutions. The results demonstrated that ITS not only enhance mobility and safety in cities but also significantly contribute to environmental sustainability and the overall quality of life for residents.

The article [3] focuses on defining the criteria important for selecting a car-sharing fleet and identifying the most suitable cars for car-sharing fleets. The study takes into account cars with traditional, electric, hybrid, and hydrogen engines. The study [4] utilizes Social Network Analysis (SNA) to examine the relationships between vehicle characteristics when making selections in Peer-to-Peer (P2P) car-sharing systems. The analysis reveals that the key factors influencing user decisions are fuel/energy efficiency, safety features, and technological advances, with a particular emphasis on driver-assistance systems, including autonomous driving capabilities.

The aim of the study [5] is to investigate carsharing from the user's perspective and determine the most influential factors affecting their choice of shared-use services, with the goal of supporting sustainable urban development. The study contributes to the broader academic discussion on carsharing and its significance for sustainable urban growth, particularly by delving deeper into carsharing practices and user motivation in Latvia; analyzing key motivational drivers for carsharing participants and sustainability considerations; and exploring generational variations influencing carsharing adoption rates.

Shared mobility issues (SMP) with the concept of shared vehicle use are rapidly becoming a global trend in many cities [6]. Typical examples of such systems include ridesharing, carpooling, taxisharing, buspooling, vanpooling, and multimodal ridesharing. An alternative transportation option added to a passenger's route could be multimodal transport, such as public buses, trains, and bikes.

Smart mobility underpins the ideas and concepts of a smart city. The impact of smart mobility is amplified by the utilization of electromobility, a global trend aligned with the principles of sustainable development and serving as a cornerstone element of smart mobility. Article [7] illustrates how these concepts evolve, the corresponding infrastructure develops, and how predictable economic factors such as energy prices might influence the deployment of electromobility in cities.

Micromobility is becoming an increasingly attractive option, especially for short-distance travel, characterized by higher sustainability and reduced risk of injuries. The article [8] provides a review of recent studies related to micromobility. Micromobile vehicles feature lower greenhouse gas emissions per passenger-km. Nevertheless, lifecycle cost analyses of micromobility vehicles may incorporate expenses tied to installing charging stations in cities.

The article [9] investigates the connection between mobility and urban public spaces, examining the influence of autonomous vehicles on urban landscapes, and proposing design strategies for autonomous cities, with a strong focus on street layouts. It demonstrates the potential of self-driving cars to reshape urban environments, while simultaneously stressing the urgency to begin planning now so that all relevant parties commit to mutually beneficial models for autonomous vehicles integration.

As primary pollution sources, cities must develop and deploy effective mitigation instruments. Review [10] 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.

Data-driven decision-support approaches are increasingly used to transform heterogeneous infrastructure indicators into structured management priorities. A digital risk-matrix and safety-management workflow has demonstrated how quantitative operational data can support transparent prioritization of infrastructure risks and management actions [11]. Although developed for airport infrastructure, the underlying decision-support principle is also relevant to urban transport systems, where mobility, environmental, safety, and service indicators must be considered jointly when evaluating alternative management scenarios.

Smart transportation systems in smart cities require supportive intelligent infrastructure. Extensive research confirms that such infrastructure enhances transport efficiency.

By "smart infrastructure", we refer not only to a system of smart traffic lights controlled by a central hub, but also to a network of video surveillance cameras equipped with facial recognition software. Data collected from these cameras would feed into a unified database for subsequent use in modeling and predicting peak load situations. In this section, we will explore the research conducted in this area.

The article [12] presents an approach to addressing sustainable development challenges through implementation of ESG framework criteria. The authors propose that robust parametric design methodologies should be employed to facilitate integrated environmental processes and address social partnership and governance challenges in uncertain conditions.

The integration of land use, transport, energy, and environmental systems (LUTEI) represents a sophisticated framework for enhancing urban sustainability. Article [13] provides a comprehensive review synthesizing diverse perspectives on this approach. The authors present an analytical framework for LUTEI implementation, featuring: integrated modeling of environmental and energy factors; equitable accessibility simulations; and transport mode choice forecasting. Their findings demonstrate that sustainable mobility infrastructure coupled with strategic urban planning can significantly enhance public health outcomes.

Owing to the high rate of motor vehicle growth, one of the most acute problems is organizing parking spaces. Parking demand usually exceeds available supply. This issue mainly stems from the scarcity of parking spots relative to the large number of vehicles on the roads.

One effective method of parking space management is improving the geometric arrangement of vehicles within the space. To maximize the number of vehicles in a parking lot, a study [14] used Monte Carlo simulation. By varying parking angles and taking into account constraints such as road width, vehicle dimensions, and required driving space, the model determines the optimal parking angle that will maximize the number of vehicles. This, according to the authors, contributes to more efficient use of available space and improved traffic management.

Study [15] points out that current building practices in Russia often neglect proper organization of parking facilities. According to the authors, with today's levels of car ownership, open-air parking lots do not adequately satisfy people's needs for temporary vehicle storage. Moreover, locating parking farther away from residential buildings increases discomfort for residents and results in expanded road networks and engineering infrastructure. Thus, designing new types of parking structures capable of achieving higher density close to housing developments becomes imperative. The paper introduces methodologies justifying the feasibility and importance of optimizing parking arrangements in established neighborhoods and newly built residential zones.

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.

Furthermore, the models will enable assessing the cross-system effects of changes in one domain on all others. For example, they could evaluate how infrastructure solutions impact environmental factors, the social sphere, and transportation system management. The DSS's open architecture will facilitate the seamless integration of modules designed to address newly emerging challenges, while also allowing assessment of their impact on other subsystems. The shared information repository will enable integrated management of urban systems and facilitate root cause analysis of adverse phenomena.

For these purposes, both micro- and macro-models can be employed to address specific tasks. For instance, AnyLogic is suitable for micromodelling. Micromodels enable scenario analysis on local road network sections under varying traffic flow conditions and from diverse perspectives (e.g., traffic flow optimization, environmental impact mitigation). Simulation modelling offers significant advantages, including: relatively low implementation costs, time efficiency, repeatable experiments and enhanced visualization and clarity. Consequently, simulation modelling stands as a premier methodology for analyzing transportation systems and identifying optimal solutions to diverse challenges, ultimately enhancing traffic flow parameters and strengthening transport system resilience.

Since all models inherently involve simplifications and deviations from real-world systems, their verification and validation are essential. Furthermore, accurate knowledge of the real system's parameters is a prerequisite for constructing a representative model. Consequently, during the initial phase, we conducted field monitoring of the real system's parameters within the designated study area. This empirical data served as the input parameters for model development. Models were typically developed in two states: "as-is" and "to-be", particularly when assessing infrastructure modifications. The "as-is" model underwent rigorous validation against the real system. This validated baseline model then formed the foundation for evaluating proposed changes using the "to-be" model. Optimization experiments on the "to-be" model were performed using the built-in optimization module, following Design of Experiments principles to efficiently explore the multi-parameter solution space.

The conceptual architecture of the proposed DSS is shown in Figure 1. The diagram illustrates an open system structure in which additional analytical or management modules can be integrated as new tasks and external conditions emerge. As evident from the presented scheme, the system features an open architecture where adding new modules - whether for emerging tasks or changing external conditions - won't cause any issues.

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. As cities expand and evolve into megacities, transportation access to major urban attractions diminishes. To maintain citizen mobility, developing efficient public transit networks becomes essential. However, given that public transport systems tend to rely heavily on subsidies and thus may struggle to meet rising demands, reliance on private vehicles increases, leading to higher rates of automobile ownership. Concurrently, the challenge of organizing adequate parking infrastructure intensifies. While diverse solutions exist, such as multi-level underground or surface parking garages and designated overnight parking zones, these options remain insufficient for addressing the daily needs of city dwellers seeking convenient parking spots near educational institutions, cultural venues, shopping malls, cafés, and restaurants. When these facilities are situated away from residential neighborhoods, sufficient parking capacity exists nearby. Conversely, inadequate parking availability causes frustration, contributes to heightened traffic congestion, and amplifies harmful emissions as drivers circle searching for vacant spots. Moreover, businesses.

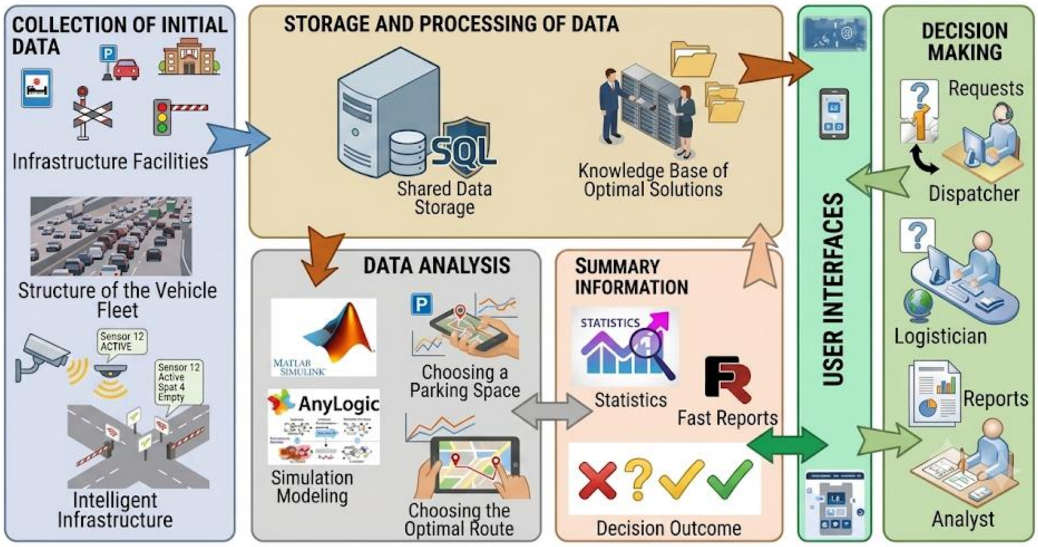

Figure 1: Conceptual diagram of the decision support system.

Suffer revenue losses if their customers opt for competing establishments offering more accessible parking arrangements. Thus, creating intelligent parking management systems is vital and achievable via simulation-based approaches.

In the article [16], we explored the possibility of optimizing urban parking space by developing a decision support system (DSS) with simulation models as its intelligent core. As an example, we presented a simulation model of parking near a fitness club.

However, since the functioning processes of public spaces can vary significantly in their models and may be algorithmically complex, the approach to optimizing parking management must also be adapted accordingly. At the same time, it is important to remember that when selecting an efficient management strategy, the aforementioned principles should be followed. These considerations guided our choice of the modeling object-a site requiring parking space optimization.

4 RESULTS AND DISCUSSION

We focused on parking spaces adjacent to educational institutions, as these sites attract multiple visitor groups potentially relying on private vehicles. The first category includes teachers who work according to the class schedule, so it is easy to predict the time when parking will be needed. The second group is parents who bring their children to classes and can occupy the parking lot while waiting for the end of lessons. The third group is guests who arrive for various events.

Therefore, it is necessary to study whether the existing parking spaces meet the needs of all user categories and, if there are difficulties, to propose a solution.

For this study, the parking area of the "City Palace of Children and Youth Creativity No. 1" preschool educational institution was selected. To construct the "as-is" model, on-site observations were conducted, with vehicle arrival rate statistics serving as the primary input data. The model was designed in both 2D (Fig. 2) and 3D (Fig. 3a and b) formats.

This site was selected for several key reasons. Initially, its location enabled commuting via public transport, yet subsequent modifications to bus and tram routes, coupled with altered timetables, rendered this mode of travel impractical. Hence, users now predominantly rely on personal vehicles or taxis, the latter being cost-prohibitive for many. Additionally, the object experiences intense pressure on parking resources due to dense scheduling across morning and evening sessions, necessitating more effective parking management strategies.

The experiment conducted with the baseline model revealed that during peak times all parking spaces would be occupied, creating significant challenges for teachers arriving at the center to conduct their scheduled classes. When forced to search for parking in nearby residential areas, teachers face multiple consequences: class schedule disruptions, increased stress for both educators and students, and negative environmental impacts

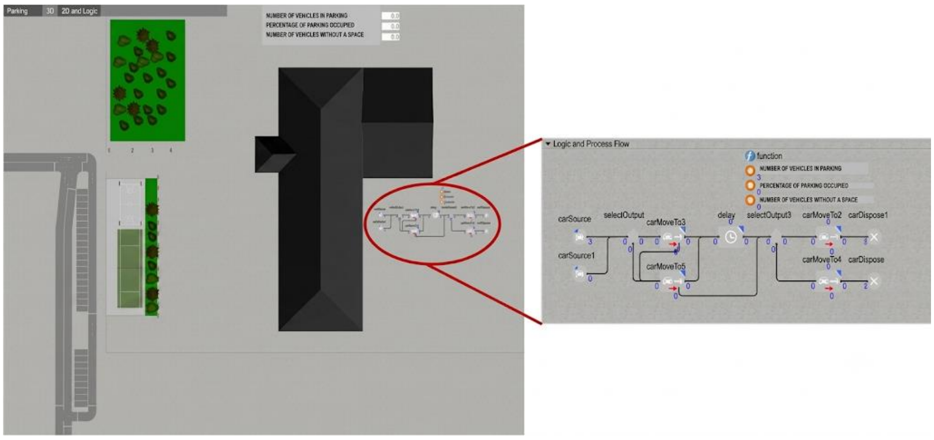

Figure 2: Structure and 2D Visualization of the Parking Area Model.

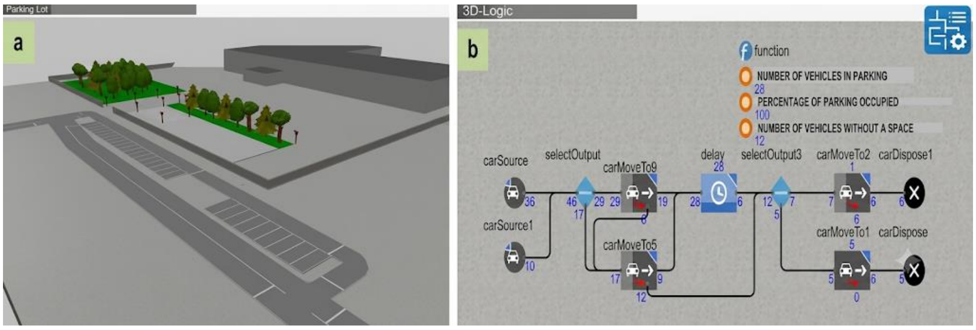

Figure 3: 3D visualization of the simulation model (a). Conducting a simulation experiment with the "as is" model (b).

The logical structure of the proposed controlled parking simulation model is presented in Figure 4.

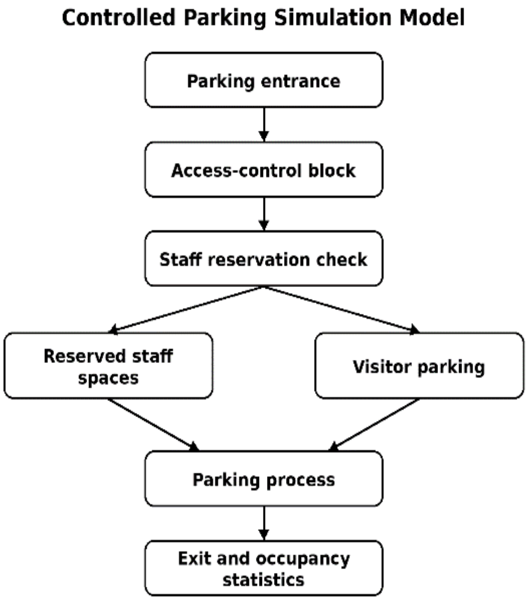

Figure 4: Logical structure of the controlled parking simulation model.

We decided to evaluate a controlled parking system approach by testing it through our "to-be" model implementation (Fig. 4, 5).

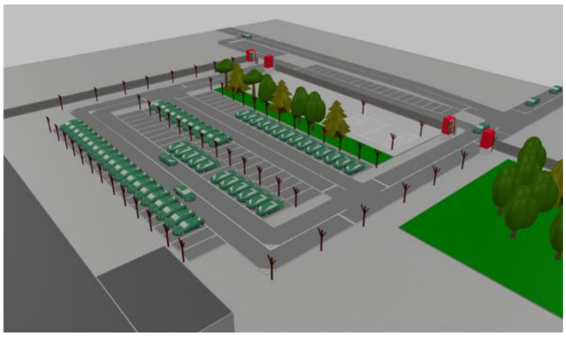

Figure 5: 3D visualization of the new simulation model.

To enhance parking management efficiency, the proposed solution involves: implementing access privilege differentiation, reserving spaces for teaching staff according to their class schedules, and dynamically managing visitor parking based on real-time demand. This conceptual framework is designed to mitigate the identified negative impacts.

For the simulation experiment, we compiled a foundational dataset containing instructors' teaching schedules, peak parking demand estimates from visitors. During experimental design, we varied two key parameters: reserved space allocation percentage, parking duration limits. The results of the two-factor simulation experiment are presented in Table 1. The maximum observed parking occupancy did not exceed 75.2% across the evaluated parameter combinations.

Table 1: Results from the two-factor experiment.

Staff parking allocations	Student and visitor parking	Parking duration	Parking occupancy
10%	90%	2 hours	70 %
10%	90%	3 hours	72.5 %
10%	90%	4 hours	75.2 %
20%	80%	2 hours	65.3 %
20%	80%	3 hours	67.8 %
20%	80%	4 hours	70.4 %
30%	70%	2 hours	60.8 %
30%	70%	3 hours	63.2 %
30%	70%	4 hours	66 %

The experiment showed that the fewer parking spaces reserved for teachers, the higher the overall occupancy rate, as guests have higher demand during peak hours. By increasing the percentage of priority reservations for teachers, we restrict access to their spots, which can lead to a decrease in overall parking occupancy. Teachers with priority occupy fewer spots and use them more predictably (according to their schedule), so in practice, the percentage of reserved spots will vary depending on the schedule.

To ensure the reliability of the baseline "as-is" model, validation was performed by comparing simulated occupancy profiles with field observations. During the morning peak hours, the number of occupied parking spaces was recorded every 15 minutes. The simulation was executed with the same arrival rates, and the average occupancy over 30 replications was compared to the observed data. The mean absolute percentage error between simulated and observed occupancy was 7.2%, indicating good agreement. Additionally, the average time to find a parking spot in the model (8.5 min) closely matched the observed average (8 min), with a relative error of 6.25%. These results confirm that the baseline model adequately represents real-world conditions. Due to the stochastic nature of vehicle arrivals and parking behaviour, each simulation scenario was replicated 30 times with different random seeds to account for variability. The objective function was to minimize the average time spent searching for parking while ensuring that staff parking demand was fully satisfied according to their schedule. Constraints included: (i) parking occupancy below 100% to avoid overflow, and (ii) reserved spaces could only be used by staff during their designated time slots. The experiment was conducted using the "Optimization" experiment type in AnyLogic 8, which employs a genetic algorithm (OptQuest) to search for optimal combinations.

It is important to note that the indirect effects of this solution will address social issues by reducing teachers' stress and anxiety levels, thereby improving their communication with students and overall teaching quality. The implementation of the parking management system has cut the average search time for a parking spot during peak hours from 8 to 1.2 minutes for teachers (an 85% reduction) and from 10 to 3.8 minutes for visitors (a 62% reduction). From an environmental perspective, this optimized parking system will decrease exhaust emissions and mitigate negative ecological impacts, as drivers no longer need to circle around searching for available spaces. Specifically, the calculated CO_2 emissions associated with parking spot searches during daytime hours (6:00-20:00, 14 hours) dropped from 5.1468 kg CO_2/day under the original system to 1.7556 kg CO_2/day with the improved system-a 65.9% reduction in CO_2 emissions.

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 [17]; emission factors per liter of gasoline consumed [18]: 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 intelligent parking management can make a measurable contribution to the sustainability, efficiency, and liveability of urban transport systems when implemented within a broader smart-city decision support framework. Using microsimulation in AnyLogic, the research developed and evaluated a parking management model for the area of a children's educational center, where competing demand from teachers, visitors, and accompanying parents creates significant pressure on limited parking resources. The proposed "to-be" model, based on differentiated access, staff priority reservations, and controlled visitor use, was shown to substantially improve parking performance compared with the baseline situation.

The obtained results confirm the practical effectiveness of the proposed approach. The optimized parking strategy reduced average parking search time during peak periods from 8.0 to 1.2 minutes for teachers and from 10.0 to 3.8 minutes for visitors, corresponding to reductions of 85% and 62%, respectively. At the same time, the environmental effect was also significant: daily CO_2 emissions associated with parking search decreased from 5.1468 kg to 1.7556 kg, representing a 65.9% reduction. These findings indicate that even local parking interventions can generate substantial operational, environmental, and social benefits when supported by data-driven modelling and optimization tools.

An important contribution of the study lies in its methodological and managerial perspective. The parking optimization task is not treated as an isolated local problem, but as part of an integrated Decision Support System with open architecture, shared data resources, and the potential to evaluate cross-system effects on urban mobility, environmental performance, and service quality. In this sense, the research illustrates how simulation-based tools can support more rational and evidence-based management of urban infrastructure, especially in contexts where direct field experimentation is costly or operationally disruptive.

The study also demonstrates the value of simulation modelling as a reliable analytical instrument. The baseline model was validated against field observations, showing good agreement in both parking occupancy and average search time. In addition, multiple replications and optimization experiments ensured that the obtained results were robust despite the stochastic nature of vehicle arrivals and parking behaviour. This strengthens confidence in the practical applicability of the proposed model as a tool for testing alternative parking policies before real-world implementation.

At the same time, several limitations should be acknowledged. The analysis was conducted for one specific parking facility and a limited set of user groups and demand conditions, which restricts direct generalization to other urban contexts. Future research should therefore extend the framework to larger parking networks, multimodal access scenarios, dynamic pricing strategies, and real-time smart parking guidance integrated with broader urban transport management systems. Overall, the study confirms that simulation-based parking optimization provides a scalable and practically grounded pathway for improving urban mobility while simultaneously delivering environmental and social co-benefits.

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