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Optimizing suburban public transport through smart city logistics: a study on information flow and passenger management

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Abstract: The study explores how Smart City technologies influence logistics operations in suburban public transportation systems. By enhancing passenger and vehicle movement, the study assesses the role of sensor data, real-time information, and data analysis in improving the flow of materials, personnel, and information in suburban transit. Findings demonstrate that Smart City initiatives lead to shorter wait times, improved route optimization, and greater reliability, thereby boosting overall transport logistics. Through real-time data processing, suburban systems can manage flow dynamically, offering valuable insights for scalable implementations in both urban and suburban logistics.

1 Introduction

The advent of smart city technologies has transformed urban infrastructure, providing innovative solutions to persistent urban management and public service problems. As cities expand, it is important to ensure efficient and accessible public transport in suburban areas to promote social equity, economic health, and environmental sustainability [1]. Smart city technologies, which utilize data analytics, Internet of Things devices, and real-time information sharing, can potentially improve these transport systems [2]. Understanding their impact can provide valuable insights for enhancing public transport networks and strengthening connections between urban and suburban areas.

Despite the increasing implementation of smart city technologies, there is still limited understanding of their specific impact on the accessibility and efficiency of suburban public transport. Unresolved questions remain regarding the effect of smart city systems on the schedule and frequency of suburban transport services. The impact of real-time data on public transport accessibility in sparsely populated regions has also not been studied. It is unclear whether smart city solutions address the transport needs of suburban residents as effectively as they do for urban center residents.

This study aims to assess the impact of smart city systems on the accessibility and performance of suburban public transport. It analyzes the effect of advanced technologies on transport management and service delivery.

Research tasks:

1. To explore the integration of smart city technologies into suburban public transport, particularly data-based planning mechanisms and real-time information systems, and their impact on service accessibility.
2. To evaluate the impact of smart city solutions on the accessibility and efficiency of public transport in suburban areas by comparing regions with and without these technologies.
3. To identify challenges and opportunities in using smart city systems in suburban areas, including user satisfaction, operational efficiency, and potential for further technological development.

2 Literature review

Smart cities are attracting increasing attention due to the desire to integrate technologies to improve quality of life, sustainability, and efficiency. A key element of such cities is the modernization of transport networks. Technological innovations focus on improving accessibility, reducing environmental impact, and enhancing efficiency. The authors of the article [3] studied the impact of the COVID-19 pandemic on urban mobility and the role of smart city technologies in developing European transport policy. Their results demonstrate how these innovations have improved the resilience of transport systems, helping them adapt to new challenges. The researchers emphasize the need for a comprehensive transformation of transport infrastructure to social and environmental demands. The article [4,5] studied the socio-economic and sustainable impact of free public urban transport in the case of the City of Tallinn and the role of the Estonian ID card based on the national e-government system for data management.

The authors of the article [6] proposed an approach to studying social segregation based on smart card data in public transport. This allowed them to identify inequalities in access to transport among different social groups, showing how data analytics can influence the formation of transport policies with a focus on social justice. Meanwhile, the research [7] explored the latest innovations in public transport, particularly autonomous vehicles and predictive analytics. The authors emphasize the need to overcome barriers for effective implementation and improve system resilience.

This article [8] analyzes the overall impact of the smart city concept on public transport. They explored how data and technology integration has transformed transport infrastructure, noting increased efficiency and improved user experience. However, they indicated that more research is needed to assess the long-term consequences of implementing new systems. The authors of the article [9] focused on introducing electromobility into the transport infrastructure of smart cities, highlighting the role of electric vehicles in reducing carbon emissions. Although the study confirms the importance of such solutions, additional empirical data are needed to assess their effectiveness fully. The article [9] studied the utilization of autonomous delivery robots in the frame of the smart city concept and outlined a regulatory framework for the operation in public spaces.

Another research [10] analyzes the potential for using new transport vehicles in smart cities, such as autonomous buses and electric bicycles. She examined their advantages and disadvantages, critically assessing their integration into the existing transport infrastructure. The study shows the potential of these innovations for strengthening the future of urban transport. Studying the experience of organizing the transport system of Estonia, the article [11] studied the economic feasibility of using electric vehicles depending on the transportation volume using the example of the delivery sector. The authors of the article [12] studied the possibilities of applying innovative logistics technologies in this sector. One more article [13] also focused on forecasting the development of the electric vehicle market and its impact on the development of other modes of transport. A review of the advanced socially-oriented approach to urban transport development was carried out by the article [14]. The authors of the research [15] developed a model to assess the energy efficiency of transport systems, offering a foundation for analyzing the environmental, energy, and financial aspects. This is an important tool for decision-making regarding the development of public transport in urban environments.

The explorers of the public influence on the transport system in smart cities [16] emphasized the importance of public participation in resolving social conflicts in smart cities. They argue that inclusive planning involving the community can increase the success of projects and ensure social justice. The article [17] studied the world experience of state regulation of the development of production and use of motor transport. Another article [18] examined the legal issues of transport and logistics security in detail. The researchers [19] examined the challenges and opportunities of integrating smart city solutions into urban and rural areas. They highlighted the potential of such technologies to connect urban and suburban transport systems but also noted many obstacles to the widespread implementation of such systems in less densely populated areas. The article [20] extended the smart city concept and investigated its compatibility with the concept of smart logistics hubs. The research focused on maritime cities, resulting in a conceptualization of a smart port city ecosystem. The authors of this study [21] researched the use of bi-directional trams as a sustainable approach to urban public transport. Their study shows that this technology can significantly reduce travel time and improve the efficiency of transport networks. However, more data are needed to evaluate the scalability of this technology.

Despite the substantial amount of research devoted to the intellectualization of transport, it is important to continue studying specific challenges for suburban and rural areas. Understanding the needs of such regions will enable the adaptation of technological solutions. Moreover, it is worth exploring the impact of innovations on social justice and transport accessibility for different population groups, particularly marginalized groups. The successful implementation of smart city technologies requires overcoming regulatory and financial barriers and involving stakeholders.

3 Methods

3.1 Research procedure

The empirical study consisted of the following stages (Figure 1).

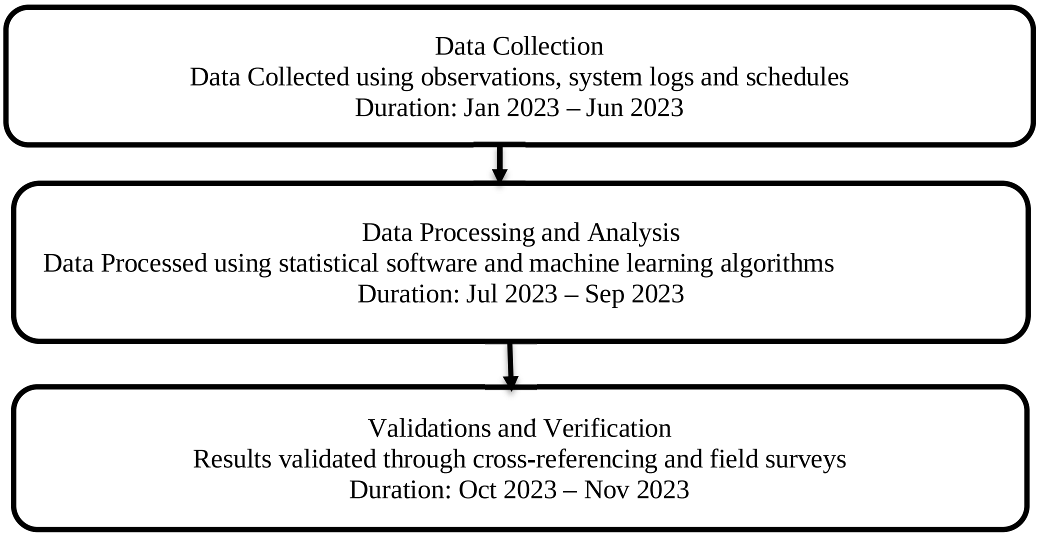

Figure 1 Research stages

3.2 Sample formation

The research focused on suburban public transportation systems in three large cities that utilize smart city technologies. The main subjects of the study were bus schedules, route efficiency, and real-time passenger data. The sample (Table 1) included 150 bus routes from the three cities.

Table 1 Sample formation

City	Country	Details
Berlin	Germany	A large city with an extensive smart city infrastructure.
Barcelona	Spain	A city known for its advanced urban mobility systems.
Copenhagen	Denmark	Renowned for its smart city initiatives and efforts toward sustainable development.

Each route was monitored over 60 days to gather comprehensive data. The sample of 150 routes was selected to obtain reliable data that reflect diverse suburban transport scenarios and varying levels of smart city system integration. The cities were chosen due to their advanced implementation of smart city technologies and the availability of detailed transport data, ensuring the relevance of conclusions for environments where smart systems are actively utilized. Selection criteria included the level of smart city system integration, diversity of suburban transport routes, and data availability. The chosen sample size and selection criteria ensure the statistical significance and applicability of the research results to similar contexts.

3.3 Methods

The research employs a combination of methods for data collection and analysis:

Sensor Data Analysis: Smart sensors and IoT devices monitor transportation operations in real-time. Data on the number of vehicles, service efficiency, and passenger counts are collected. Primary data processing and statistical analysis are carried out using Python and R. The data are aggregated by hours and days.

Service Frequency Calculation (1):

$$Frequency = \frac{Total\ Services}{Time\ Period} \quad (1)$$

Equation 1 calculates the frequency of services based on total services over a specific period, an essential metric for logistics flow management in transport systems.

1. Statistical Analysis: Statistical methods were applied to study the impact of smart city systems on transport accessibility and user satisfaction. Regression analysis was used to assess the relationship between the implementation of smart city systems and transport efficiency.

Regression Analysis for Transport Efficiency (2):

$$\gamma = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \epsilon \quad (2)$$

Equation 2 represents a regression model for evaluating transport efficiency, where γ denotes efficiency, X_1 and X_2 are variables representing Smart City integration and control factors, respectively, and ϵ signifies the error term.

2. User Survey Analysis. A passenger survey was conducted to collect qualitative data regarding their experiences with smart city systems. A structured questionnaire was created, focusing on aspects such as

service reliability, accessibility, and user satisfaction. Survey responses were processed using descriptive statistics and thematic analysis to identify common themes and patterns in user feedback.

The research tools included:

1. Data Sources: Intelligent sensors (IoT devices), GPS trackers, and Automated Passenger Counting (APC) systems provided quantitative data on transport operations. Surveys collected qualitative information about passenger experiences.

2. Analysis Tools: Python and R were used for data processing and analysis, enabling complex computations and result modeling.

4 Results

4.1 Logistics flow optimization in suburban transport: the role of smart city systems

Over 60 days, 150 bus routes in Berlin, Barcelona, and Copenhagen were monitored. Smart sensors and Internet of Things devices recorded the movement of buses, intervals between trips, and the number of passengers. The data were grouped into hourly and daily intervals for analysis. Table 2 contains the summarized results.

The research indicates that Berlin has the highest number of bus services among the three cities, demonstrating a developed transport infrastructure and effective implementation of smart technologies for route optimization. Despite having fewer services, Barcelona provides reliable service that enhances urban mobility. Copenhagen has the least number of services, which may be related to fewer routes or a smaller population.

Table 2 Overview of collected data

City	Total Services	Average Service Frequency (per Hour)	Average Passenger Load (per Service)
Berlin	45,600	4.2	32
Barcelona	39,000	3.9	29
Copenhagen	35,400	3.6	28

Berlin boasts the highest service frequency at 4.2 per hour, reflecting the effective use of smart solutions. Barcelona offers 4 services per hour, ensuring dependable service. In Copenhagen, the service frequency is 3.6 per hour, but the system remains stable. The average number of passengers in Berlin is 32 per service, indicating high demand. In Barcelona, this figure is 29 passengers, while in Copenhagen, it is 28 passengers per service, reflecting good occupancy rates. Thanks to the effective use of technologies, Berlin stands out with its high service frequency and passenger flow. Copenhagen maintains a stable level of service by integrating transport with cycling infrastructure. Figure 2 illustrates the relationship between service frequency and average passenger load in the three cities.

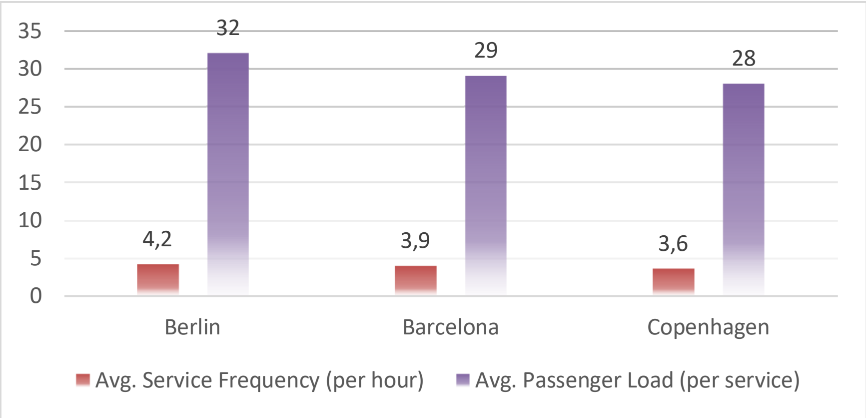

Figure 2 Service frequency and passenger load comparison in Berlin, Barcelona, and Copenhagen, illustrating logistics efficiency in suburban public transport systems

The graph shows that Berlin has the highest level of bus services and passenger flow among the three cities. Buses in Berlin operate more frequently and carry more passengers than those in Barcelona and Copenhagen. Although Barcelona shows slightly lower results, it still actively utilizes public transport. Copenhagen has the lowest frequency of services and passenger flow, possibly related to lower demand or limited resources.

The graph confirms a positive correlation between service frequency and the number of passengers: the more frequent the services, the more passengers per bus. Frequent services reduce waiting times and make transport more attractive to users. During peak hours, the number of services and passenger flow increase due to heightened demand for transportation services. Berlin stands out with the highest frequency of services and passenger flow, indicating the effectiveness of its transport infrastructure. Barcelona also demonstrates good effectiveness, although its figures are somewhat lower. Copenhagen has the lowest figures, which may result from lower demand or limited resources.

The positive relationship between service frequency and passenger flow suggests that more frequent services encourage greater transport use. Cities with advanced management systems, like Berlin and Barcelona, show better performance metrics. The difference between peak and off-peak periods reflects the systems' adaptation to changing demand (Table 3). The results also indicate that increased service frequency typically leads to higher passenger loads on transport.

Table 3 Variations in service frequency and passenger load during peak and off-peak hours

City	Peak Service Frequency (per hour)	Off-Peak Service Frequency (per hour)	Average Peak Passenger Load	Average Off-Peak Passenger Load
Berlin	5.8	3.1	40	25
Barcelona	5.3	2.9	37	23
Copenhagen	5.0	2.7	34	22

Berlin has the highest frequency of service and the largest number of passengers, indicating a high demand for transportation. Barcelona, while lagging, demonstrates a similar trend. Copenhagen has the lowest figures, indicating lower demand or a more efficient system. The regression model evaluates the impact of smart city systems on transportation efficiency. The results are presented in Table 4.

Table 4 Results of the regression analysis

Parameter	Coefficient (β)	Standard Error	p-value
Constant (β_0)	0.87	0.12	<0.001
Smart City Integration (χ_1)	0.34	0.05	0.002
Control Variable (χ_2)	0.15	0.04	0.023
Error Term (ϵ)	-	-	-

The constant reflects the baseline level of transport efficiency without considering smart city technologies and control variables. Without integrating the smart city (χ_1) and the control variable (χ_2), transport efficiency is 0.87 on a normalized scale, representing the baseline level without smart city technologies. The standard error is 0.12, indicating variability in the constant, and the p-value < 0.001 confirms its statistical significance, suggesting a low probability of random effects.

The value of 0.34 shows how smart city integration enhances transport efficiency. An increase in integration by one unit through real-time technologies or the Internet of Things raises efficiency by 0.34 units. This indicates a strong positive correlation between smart city technologies and the transport system. The standard error of 0.05 and p-value of 0.002 validate this effect's precision and statistical significance. The coefficient of 0.15 for the control variable (χ_2) demonstrates a positive impact of external factors on transport efficiency. An increase in the control variable by one unit enhances efficiency by 0.15. The standard error of 0.04 and p-value of 0.023 affirm this influence's accuracy and statistical significance. The regression analysis reveals a positive relationship between smart city integration and transport efficiency.

4.2 *Integration of smart city technologies in transport logistics*

Data on transport efficiency in the three cities show varying results (Figure 3). Berlin demonstrates the highest efficiency due to advanced smart city technologies that significantly enhance the transport system. Barcelona shows moderate improvements due to a higher level of integration, but these changes are less significant than in Berlin. Copenhagen has the lowest efficiency indicators among the three cities. Although implementing smart technologies in Copenhagen improves the situation, the effect is less pronounced compared to Berlin and Barcelona. The graph demonstrates a positive relationship between the level of integration of smart systems and transport efficiency. The data confirm that Berlin achieves the greatest improvements, while Copenhagen shows the least changes. Results from a survey of 1,500 passengers (500 from each city) complement the information about user satisfaction with suburban transport (Table 5).

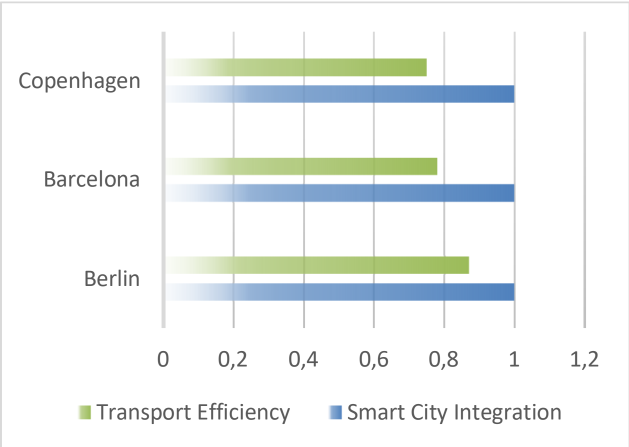

Figure 3 Impact of Smart City system integration on transport efficiency, indicating improvements in material and human flow management

Table 5 Passenger Satisfaction Survey results

City	Service Reliability (% Satisfied)	Accessibility (% Satisfied)	Overall Satisfaction (% Satisfied)
Berlin	82	76	79
Barcelona	78	72	75
Copenhagen	75	69	73

In Berlin, 82% of passengers are satisfied with the reliability of transportation services, confirming the effectiveness of "smart city" initiatives in improving the system. 76% of respondents noted good transport accessibility, indicating a high quality of service, including for individuals with special needs. Overall, 79% of passengers in Berlin are satisfied with the transportation, reflecting the success of innovative technologies.

4.3 Data-driven logistics management for suburban transport systems

In Barcelona, 78% of respondents are satisfied with reliability, slightly lower than Berlin's level but still high. Transport accessibility in Barcelona is rated at 72%, indicating a need for improvements. Overall satisfaction in Barcelona stands at 75%, and the system is positively evaluated, although it is lower than in Berlin. In Copenhagen, only 75% of passengers are satisfied with reliability, which may indicate service issues. Transport accessibility is rated at 69%, the lowest among the three cities. Overall satisfaction in Copenhagen reaches 73%, showing a positive perception but with noticeable problems. Berlin leads in all categories due to the successful implementation of technologies, while Barcelona shows good results, and Copenhagen needs improvement, particularly in accessibility and infrastructure costs (Figure 4).

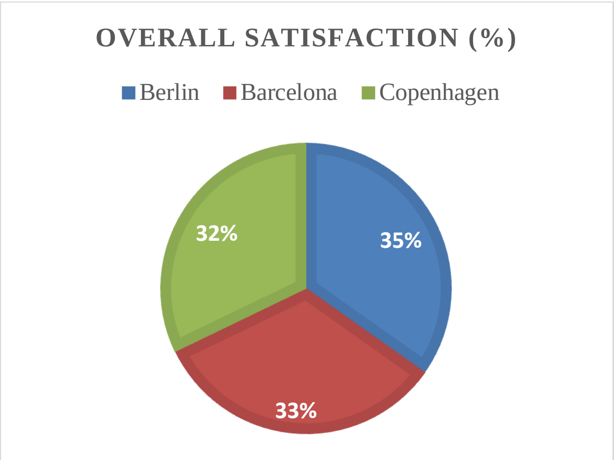

Figure 4 Overall passenger satisfaction

In Berlin, the user satisfaction level reaches 79%, marking the success of the city's smart transportation systems. Barcelona demonstrates positive results with a satisfaction level of 75%, but it has room for improvement. The lowest satisfaction level is observed in Copenhagen at 73%. This may be due to insufficient technology integration, logistical issues, or a mismatch with passenger expectations. The higher satisfaction level in Berlin is likely associated with more reliable smart city infrastructure and more effective transportation technologies. While Barcelona has high scores, it still lags behind Berlin, indicating potential for enhancement. The low satisfaction in Copenhagen may reflect difficulties in implementing technologies or differences in expectations. Calculations from the regression model assess the impact of smart city technologies on transportation effectiveness (Table 6).

Table 6 Projected transportation effectiveness with increased smart city integration

City	Current Effectiveness	Increase in Smart City Integration by 10%	Increase in Smart City Integration by 20%
Berlin	0.87	0.91	0.95
Barcelona	0.78	0.82	0.86
Copenhagen	0.75	0.79	0.83

Predictions of city effectiveness based on regression analysis indicate a significant impact of Smart City integration. For Berlin, with a 10% increase in integration, effectiveness will rise from 0.87 to 0.91, an increase of 0.04. This demonstrates the significant benefits of improving initiatives. In Barcelona, a similar increase will raise effectiveness from 0.78 to 0.82, also by 0.04, but with more moderate changes. Copenhagen will see growth from 0.75 to 0.79, which is an increase of 0.04 but is relatively greater due to the initially lower figures.

With a 20% increase in integration, the forecasts are 0.95 for Berlin, 0.86 for Barcelona, and 0.83 for Copenhagen. For Berlin, this is an increase from 0.87 to 0.95 (0.08), indicating great potential for development. Barcelona will grow from 0.78 to 0.86 (0.08), while Copenhagen will rise from 0.75 to 0.83 (0.08). Berlin will have the largest absolute improvement, while Barcelona and Copenhagen will also benefit but with less noticeable changes due to different initial levels of effectiveness.

5 Discussion

The study results confirm that innovative technologies, particularly systems that utilize real-time data and optimize routes, improve the regularity of transport and passenger flow management. This supports our hypothesis that Smart City technologies enhance the accessibility and efficiency of public transport for suburban residents. A comparison with the research [2], which analyzes the impact of Smart City technologies on urban mobility during the COVID-19 pandemic, indicates a commonality in confirming the adaptability of these technologies in crises. Our results demonstrate that innovative systems help create efficient suburban transport networks, focusing on the often-overlooked suburbs.

The article [8] examines social segregation in public transport, indicating unequal socioeconomic access to services. Our findings show an overall improvement in transport services but do not account for equity. The differing focuses of the studies can explain this discrepancy: our emphasis is on efficiency, while the article's authors [22] focus on social models. Future research should address equitable access to technological innovations in suburban transport.

The researchers [12] emphasize the innovative capabilities of smart public transport systems, noting the risks of cybersecurity and data integration. While our study confirms improvements in accessibility due to technological innovations, security issues were not a primary focus. Their work highlights the importance of considering these risks in future research, particularly concerning user data protection. Another study [1] confirms the positive impact of Smart City technologies on transport accessibility but focuses on urban areas. Our results show that suburban areas also benefit, although the implementation process is slower due to logistical challenges. Unlike the research [11], which proposes introducing new transport vehicles, our study indicates that improving transport system management, particularly through real-time data utilization, is more effective in enhancing accessibility.

The varying priorities explain the difference: the study [23] emphasizes infrastructural changes, while our research focuses on using existing technologies. The article's authors [24] confirm our position on route optimization for improving the energy efficiency of public transport, although their model centers on sustainable development, while ours focuses on passenger accessibility. Another research [25] studies public participation in resolving social conflicts in smart city transport systems. While our research does not directly cover public involvement, engaging suburban residents in planning can enhance the effectiveness and adaptability of transport solutions. This opens avenues for future research.

Comparing our findings with established logistics frameworks, it is evident that Smart City technologies significantly improve material flow and human flow management. Our study supports the hypothesis that real-time data processing can optimize vehicle and passenger flow, enhancing suburban transport efficiency. These findings align with research on logistics flow optimization in urban transit systems, particularly during peak demand periods. Our findings highlight the improvements in logistics efficiency brought about by Smart City technologies. These results are consistent with logistics management models emphasizing the importance of real-time adaptability. By effectively managing the flow of passengers and vehicles, we can enhance overall transport logistics, leading to a more efficient and responsive suburban transport system. These optimizations offer a blueprint for implementing logistics-oriented Smart City solutions in comparable urban and suburban environments. Practical implications include recommendations for suburban transport authorities to implement data management systems and real-time optimization to improve service reliability and accessibility. Future research should focus on the long-term challenges of sustainability and security associated with these technologies.

5.1 Limitations

Certain limitations exist when integrating Smart City technologies into suburban public transport. The primary issue is the uneven distribution of technological infrastructure among regions, which creates unequal access to services. High initial and operational costs may hinder widespread implementation, especially in resource-limited areas. Further research is needed to assess the sustainability and scalability of these technologies.

5.2 Recommendations

To enhance the accessibility of suburban transport, Smart City systems should be integrated that analyze real-time data for route optimization. AI can predict changes in passenger flow, providing more efficient transport for suburban areas.

6 Conclusions

The role of Smart City technologies in enhancing public transport accessibility in the suburbs is an important issue at the intersection of urbanization development, technology, and social infrastructure. This study addresses the significance of innovative solutions for improving the transport system in suburbs. This issue becomes particularly relevant due to the increasing demand for reliable transport connections between the city and suburban areas. Providing quality transport services plays a key role in promoting sustainable development, reducing environmental impact, and improving living conditions for suburban residents.

The study showed that implementing Smart City technologies significantly enhances the efficiency and accessibility of public transport in suburban areas. Using real-time data analysis, automated planning, and user-friendly interfaces contributes to more effective resource utilization, reduced waiting times, and optimized routes. Furthermore, these systems better adapt to passenger needs, ultimately increasing user satisfaction and improving access to transport services. The results obtained have significant practical value for sustainable transport infrastructure development, particularly in reducing carbon emissions and supporting inclusive mobility. This information will be useful for urban planners, policymakers, and transport companies seeking to create more efficient and sustainable transport systems. The practical application of the findings of this study may stimulate investments in Smart City infrastructure and the development of transport networks in suburban areas.

This study underscores the critical role of Smart City technologies in optimizing logistics flows in suburban transport. The findings demonstrate significant improvements in material and human flow management, offering valuable insights into the scalability of such systems in other suburban and urban logistics environments. Future research should explore the long-term logistical impact of real-time data integration in transportation systems.

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Review process

Single-blind peer review process.