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Enhancing Urban Transport Environmental Performance with Technology and Innovation

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Abstract
This article addresses the challenges faced by urban transport systems, particularly focusing on solutions that can mitigate the excessive noise and pollution generated by transportation activities in cities. The authors examine both existing initiatives and emphasize the need for comprehensive solutions that integrate various approaches into a cohesive system. This integrated system would enable the seamless use of multiple modes of transport through advanced organizational strategies and information and communication technology solutions. The primary aim of this article is to present a review of selected strategies and technologies that have the potential to reduce the harmful environmental impacts of urban transport. By evaluating these solutions, the authors highlight how they can be effectively implemented to enhance the environmental performance of urban transportation systems. The review covers a range of approaches, from isolated initiatives aimed at addressing specific issues to more holistic strategies that involve the integration of different transport modes and the application of information and communication technology. The authors argue that while individual initiatives can provide short-term relief, the most significant and sustainable improvements will come from systems that allow for coordinated and flexible transportation options, which are crucial for reducing noise, emissions, and overall environmental degradation in urban areas. Through this analysis, the article contributes to the ongoing discourse on sustainable urban development, offering insights into how cities can transition towards greener transport systems. The findings suggest that policymakers and urban planners should prioritize the development of integrated transport solutions that leverage technology and organizational innovation to address the complex challenges of urban transportation. In conclusion, the article underscores the importance of adopting a multi-faceted approach to urban transport planning, one that not only addresses immediate environmental concerns but also lays the groundwork for a more sustainable and resilient urban transport infrastructure.
Keywords: Urban Transport, Environmental Impact, Sustainable Development
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1. INTRODUCTION

The multidimensional nature of the socio-economic and environmental crises, along with their widespread effects, has led to a global emphasis on issues related to sustainable development. This shift in policy and focus has had a significant impact across all sectors of the market economy. However, sustainable development holds particular importance in the transport sector, which serves as an economic integrator. Transport not only plays a key role in supporting sustainable development, but also actively shapes it through its operations (Eberts, 2015: 1). Currently, there is growing interest in incorporating sustainability into the planning and functioning of transport systems, as highlighted by Litman and Burwell (2006: 331-347). The drive toward sustainability in transport seeks to balance various factors, including reducing environmental impact, improving efficiency, and maintaining economic viability. This balance can be understood through two primary groups of considerations: mobility issues and transport accessibility issues, as discussed in the White Paper 2011. Mobility pertains to the ability to move goods and people efficiently, while accessibility focuses on ensuring that transport networks provide adequate access to services, markets, and opportunities for all. The analysis of sustainable transport can be approached from either a narrow or broad perspective. A narrow view typically focuses on specific issues, such as emissions reduction or energy efficiency, while a broader perspective encompasses a wider range of factors, including social equity, economic development, and long-term environmental stewardship (Pawłowska, 2013: 198). Both perspectives are essential for developing transport systems that not only meet present needs but also contribute to the broader goals of sustainable development, ensuring that future generations can enjoy the same levels of mobility and accessibility without compromising the environment.

Mobility and accessibility are key features that influence the social acceptance of transportation systems. However, to achieve truly sustainable transport, these factors must be carefully balanced with environmental considerations. When access to transportation is limited for certain groups, it can lead to decreased interest in collective transport options, such as public transit, which may, in turn, result in increased reliance on personal vehicles. This shift can have negative environmental

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consequences, such as higher emissions and increased congestion, particularly in affected areas. From the perspective of a narrow approach to sustainable transport, environmental aspects take center stage. This includes focusing on public health and its protection, minimizing pollutant emissions, reducing noise and vibrations, and ensuring the responsible use of natural resources (Karl-Henrik et al., 1996). In this context, the goal is to mitigate the negative impacts of transport on the environment while promoting practices that contribute to long-term sustainability. On the other hand, a broader approach to sustainable transport views it as part of a larger, integrated system that balances environmental, social, and economic factors. As Pawłowska (2013: 201) suggests, sustainable development of transport is not solely about reducing environmental harm but also about creating a transport system that fosters accessibility while being environmentally responsible, socially acceptable, and economically viable. According to the OECD (2004: 45), a sustainable transport system ensures accessibility in a manner that respects the environment, takes public opinion into account, and remains economically feasible. This holistic approach highlights the need for transport systems to be designed in ways that not only reduce their ecological footprint but also serve the needs of society and support economic growth. Ultimately, the goal of sustainable transport is to achieve a balance where environmental, social, and economic priorities coexist, ensuring the system's viability for current and future generations. In this research work, the authors concentrated on the narrow approach to sustainable transport development, specifically focusing on the environmental aspects of balancing transportation within urban systems. The primary objective of the study was to explore and present potential strategies that could be implemented to develop a fully integrated, environmentally sustainable, and advanced urban transport system. The research highlighted not only individual transport initiatives aimed at reducing environmental impacts—such as improving energy efficiency, reducing emissions, and promoting eco-friendly transport modes—but also emphasized the necessity of integrating these solutions into a coherent system. This integration requires the use of various organizational strategies and ICT (Information and Communication Technology) solutions to ensure that different transport initiatives work seamlessly together. By combining these diverse approaches, the study aimed to demonstrate how urban transport systems can be transformed to better support sustainability goals while meeting the practical demands of urban mobility. In sum, the work showcases the importance of creating an interconnected transport network that prioritizes environmental sustainability, utilizing innovative technologies and organizational methods to form a cohesive, eco-friendly urban transport system.

2. DISCUSSION

One of the most critical factors in achieving balanced and sustainable transport systems in urban areas is changing traveler behavior and offering a viable alternative to private car use. The steady rise in the number of passenger cars on city road networks, coupled with the limited ability to further expand infrastructure, has resulted in significant congestion—particularly in city centers. This situation exacerbates other negative environmental impacts, such as increased emissions of harmful pollutants and higher noise levels, both of which are detrimental to urban living conditions. One of the key solutions to this problem is the implementation and promotion of efficient urban public transport systems that cater to the needs of city travelers. Public transportation options—such as buses, trams, trolleybuses, city railways, and subways—are more environmentally friendly than private cars and help reduce the volume of traffic in urban areas. Even though some buses may emit more exhaust compared to individual cars (depending on the technology used), they offer far greater efficiency in terms of passenger capacity. For example, a single bus can transport as many people as 70 cars within the city and 30 cars outside urban areas (Pawlak and Pawlak, 2010: 6). This illustrates the significant impact that public transport can have on reducing the number of vehicles on the road, thus alleviating congestion and its associated environmental effects.

Furthermore, in recent years, the adoption of electric buses has increased in many cities (as shown in Figure 1). These electric buses, which produce zero emissions at the point of use, further reduce the environmental footprint of urban transport systems. The shift towards electric public transport is a key step in making cities cleaner and more sustainable. Therefore, public transport, especially with the integration of electric vehicles, represents a far less harmful alternative to the environment compared to individual car use, and it plays a central role in balancing urban transport systems in favor of sustainability. Statistics on the adoption of electric buses in urban transport systems highlight the significant environmental and social benefits that this technology can deliver. According to the report "Alternative Fuels in Public Transport" published by The Denmark Congress of Alternative Fuels (PKPA, 2018: 11), electric buses offer a better operational range, reduce noise pollution, and contribute significantly to lowering emissions of CO_2, nitrogen oxides (NO_x), sulfur compounds, and particulate matter (PM). These reductions in emissions help mitigate urban air pollution, contributing to better public health and overall environmental quality. One of the key challenges in organizing effective electric bus solutions is understanding the actual needs of the population and designing appropriate timetables, routes, and stops to increase the competitiveness of public transport. Urban transport organizers and local authorities must ensure that public transportation is efficient, reliable, and accessible. To achieve this, they must carefully assess transportation demand, optimize routes, and ensure that public transit offers a viable alternative to private vehicles (Janecki, Krawiec, and Sierpiński, 2010: 112). The goal is to encourage more citizens to choose public transport by making it more convenient and aligned with their mobility needs, ultimately improving its competitiveness compared to private car use.

In some cities, more advanced solutions, such as the Bus Rapid Transit (BRT) systems, are being implemented to enhance the efficiency of public transport. The BRT system consists of a network of buses—often electric or powered by alternative fuels—running on dedicated lanes, separated from regular traffic. This infrastructure includes metro-like bus stops, real-time traffic control systems, and passenger information systems to ensure smooth operation (Levinson et al., 2003: 4-5). The BRT system is designed to minimize delays caused by traffic congestion and improve the overall reliability and speed of public transportation. The introduction of BRT systems aligns closely with the goals of sustainable transport development by reducing emissions, easing congestion, and promoting energy-efficient transit options. BRT systems can significantly enhance urban mobility while lowering the environmental impact of transport, making them a critical component of modern, sustainable urban transport strategies. By integrating such systems into urban planning, cities can better meet the demands of their growing populations while advancing their sustainability agendas.

The first Bus Rapid Transit (BRT) system, launched in 1974 in Curitiba, Brazil, and known as "Rede Integrada de Transporte" (Integrated Transportation Network), set a precedent for efficient urban transportation (Cervero, 1998: 265-296). Since then, BRT systems have grown in popularity and have become a common feature of urban transport infrastructure worldwide. As of 2018, BRT systems were operational in 169 cities around the globe (BRT Data 2018). One of the key advantages of BRT is its ability to reduce traffic congestion by offering an ecological alternative to traditional modes of transport, such as private cars. Additionally, BRT systems provide fast and efficient transportation akin to metro or high-speed trains but at a much lower cost for cities (Levinson et al., 2003: 5). A crucial feature of BRT systems is their use of dedicated lanes, which reduce emissions compared to public transport systems that share lanes with private vehicles. Separate lanes enable BRT buses to maintain faster travel times, reduce congestion, and minimize the environmental impact. Furthermore, many modern BRT systems have embraced environmentally-friendly technologies, including buses powered by electricity, LNG (liquefied natural gas), CNG (compressed natural gas), and hybrid systems. These energy-efficient vehicles further enhance the ecological benefits of BRT systems, making them a sustainable solution for urban mobility (BRT Data 2018).

In addition to BRT, bicycles offer a highly sustainable mode of transport with high mobility and significantly lower costs compared to cars. In fact, the cost of cycling is more than 24 times lower than driving a car (Berdo, 2006: 66). Experiences from countries like Denmark, the Netherlands, and Germany demonstrate the positive impact of restricting car traffic on specific streets in favor of cyclists and pedestrians (Wesołowski, 2008: 144; Tundys, 2008: 207, 228). These car-free streets have seen thriving businesses, such as shops and cafes, and have encouraged people to shift their transportation habits away from cars toward more sustainable alternatives. By creating environments where walking and cycling are prioritized, cities can promote healthier, cleaner, and more vibrant urban spaces. Another approach to fostering environmentally-friendly urban transport is through the sharing economy. The growing popularity of shared mobility solutions has led to an increasing number of short-term rental options for residents, including car-sharing services where vehicles are rented by the minute. This shift towards shared transport options reduces the need for private car ownership, contributing to reduced traffic and lower emissions in urban areas. One of the most notable innovations in the sharing economy is the rise of city bike rental systems, which combine the convenience of cycling with the principles of shared mobility. Denmark has been a leader in this area, with its city bike rental systems gaining widespread popularity (Czech et al., 2017: 161-169). Although bike-sharing systems date back to 1965, they have seen a resurgence in recent years, particularly with the development of next-generation systems. The latest advancement, the 5th generation dock-less bike-sharing systems, has made cycling even more accessible by allowing users to rent and park bikes without the need for fixed docking stations (Chen et al., 2018: 5-13). These systems have become increasingly common in urban transport networks, providing an eco-friendly and flexible transportation option for city dwellers.

BRT systems, cycling infrastructure, and shared mobility solutions represent a comprehensive approach to achieving sustainable urban transport. By integrating these diverse modes of transport, cities can reduce their environmental impact, alleviate congestion, and promote healthier, more active lifestyles among residents. The success of these initiatives in cities across the globe demonstrates the potential for innovative transport solutions to transform urban mobility and contribute to broader sustainability goals. The implementation of bicycle transport systems is supported by various factors beyond its well-known health benefits and status as the most environmentally friendly form of transportation. Bicycles provide access to areas where motorized traffic is restricted, making them highly adaptable to dense urban environments. They also play a crucial role in improving air quality in city centers by reducing the reliance on cars, which are major contributors to pollution. Moreover, bicycles help alleviate pressure on congested road networks, enhance transport accessibility, and serve as an important complement to public transport. In cities that integrate bike-sharing programs, the presence of bicycles not only makes the city more appealing, particularly for tourists, but also reduces the need for costly road network expansions. Consequently, bicycles become a vital element in creating an integrated and sustainable urban transport system (Czech, Turoń, Urbańczyk, 2017: 103-111).

Bike-sharing systems, in particular, contribute to making travel more environmentally friendly. A notable example is the bike-sharing system in Shanghai, which, in 2016, reduced $CO2$ emissions by 25,240 tons and saved 8,358 tons of petrol (Zhang and Mi, 2018: 296-301). These significant reductions highlight the environmental impact of large-scale bike-sharing programs, as they help cities lower carbon emissions and decrease reliance on fossil fuels. By integrating bike-sharing into urban transport networks, cities can take meaningful steps toward achieving their sustainability goals, enhancing both the environmental quality and livability of urban spaces. Another viable strategy to make urban transport systems more environmentally sustainable is to invest in an increasing number of electric vehicles (EVs). A key document outlining the

European strategy on alternative fuels, titled "Clean Power for Transport" (2013), highlights the risks associated with Europe's heavy dependence on oil for mobility and transport. The document emphasizes the urgent need for transformative changes across all transport modes to address long-term energy and sustainability needs. Among the alternative fuels identified in the strategy are LPG, natural gas (LNG and CNG), electricity, liquid biofuels, and hydrogen. Currently, many countries are accelerating efforts to develop electromobility, with Denmark, for instance, implementing a Plan for the Development of Electromobility (2016-2025). Electric vehicles, despite their higher initial purchase price compared to conventional vehicles, represent an important alternative for reducing dependency on fossil fuels and minimizing environmental impact. Alongside their well-known environmental benefits—such as zero tailpipe emissions—electric vehicles are increasingly supported by targeted policies that offer various incentives to owners (Himmel et al., 2016: 472-484).

Governments across Europe have introduced special privileges for EV owners as part of their drive to promote electromobility. These privileges include access to bus lanes, exemptions from taxes and tolls, entry into city centers with restricted traffic or car-free zones, and free parking in areas where traditional vehicles are required to pay. In addition, many cities provide free charging stations for electric vehicles (Longo et al., 2015: 439-445). These incentives help to offset the higher upfront costs of electric vehicles and encourage more consumers to switch to greener alternatives, ultimately contributing to the reduction of urban pollution and the promotion of sustainable urban mobility. By investing in electric vehicles and offering supportive policies, cities can reduce their reliance on oil, lower greenhouse gas emissions, and create more sustainable and accessible urban transport systems. The rapid rise in the popularity of car-sharing systems reflects a growing interest in the development and expansion of such services. Car-sharing is increasingly becoming a viable alternative to traditional taxis (Kubik et al., 2018: 923-930), offering consumers more flexibility and cost-effectiveness while contributing to the reduction of urban congestion and pollution. In Denmark, the car-sharing market has seen notable growth since the first system was introduced in 2016, with six operators now providing services (Turoń and Czech, 2018: 17-26). This growth mirrors broader trends across Europe, where car-sharing services are also gaining momentum.

An analysis of the European car-sharing market based on data from 40 rental companies and 187 vehicles reveals that 72% of the cars available for rent are powered by conventional internal combustion engines, while 28% of the fleet consists of vehicles with alternative drive systems, including hybrid and electric models (Turoń et al., 2018: 412-414). This demonstrates a gradual shift toward more environmentally friendly options, although conventional cars still dominate the market. The increasing popularity of car-sharing services and the integration of electric vehicles is paving the way for more advanced transportation technologies, particularly autonomous vehicles. The intensive development of both car-sharing and electric mobility is seen as a precursor to the eventual introduction of autonomous cars, which many believe will revolutionize urban mobility by improving efficiency, safety, and sustainability (Czech et al., 2018: 15-22). As the car-sharing industry continues to grow, it is likely to play a key role in the transition toward autonomous vehicle fleets, contributing to cleaner, smarter, and more efficient urban transport systems.

3. SOLUTIONS

The organizational and infrastructural solutions mentioned earlier, regardless of their specific selection and structure, require a crucial additional element: the effective transmission of information. The dissemination of real-time information through modern technologies is indispensable for both educating the public and improving the perception of alternative travel solutions. One of the most commonly implemented systems is dynamic passenger information, which provides real-time updates on public transport operations. Dynamic passenger information systems deliver critical data, such as current road conditions and delays, allowing passengers to make informed decisions about their travel plans. This technology can function independently or be integrated into more comprehensive systems like Intelligent Transport Systems (ITS) (Paradowska, 2011: 391). Such information systems build trust in public transport by keeping passengers informed about potential disruptions or delays, thus improving the overall user experience. For instance, even if a bus is delayed, passengers are more likely to maintain confidence in the service if they are informed about the situation in real time. Moreover, dynamic passenger information systems enhance the readability of timetables, making it easier for passengers to plan their journeys. Although these systems do not have a direct environmental impact, they can lead to behavioral changes that indirectly support sustainability. By providing accurate and timely information, these systems can encourage more people to choose public transport over private vehicles, thereby reducing traffic congestion, emissions, and overall environmental impact. In this way, dynamic information systems contribute to the broader goals of sustainable urban mobility by promoting public trust and encouraging a shift toward more eco-friendly travel options.

Solutions that support the operation of urban transport systems also include methods aimed at facilitating access to transport services, making the experience more seamless and user-friendly. For instance, technologies like QR codes and card readers significantly streamline the process of purchasing tickets or accessing services. These solutions reduce the time required to acquire transportation services and eliminate the need for paper-based documentation, such as traditional tickets. QR code identification, in particular, is widely used in urban bike- and car-rental systems, enhancing convenience for users by allowing quick and easy access to these services. Another technological advancement in urban transport systems is the implementation of the city card, which provides a more integrated solution for urban mobility. Unlike mobile applications, city cards allow users to access any mode of public transport offered by the city—whether it's buses, trams, subways, or rental services—by simply swiping the card (Figure 7b). In addition to transport services, city cards often enable the purchase of other urban services, such as tickets for cultural events or city attractions. These cards are typically rechargeable at kiosks or machines conveniently located at public transport stops, further enhancing accessibility. Both QR code systems and city cards assist travelers by simplifying access to transport services and reducing wait times, which ultimately speeds up the process of starting a journey. By making public transport more convenient, these technologies indirectly encourage changes in travel behavior, fostering a shift away from private vehicles and toward more sustainable, communal forms of transport. As a result, these innovations not only improve the user experience but also contribute to broader goals of sustainable urban mobility by making public transportation a more attractive option.

4. CONCLUSIONS

Choosing the most appropriate set of solutions for improving urban transport in a given area is a complex and nuanced process. No single solution will suit all contexts, as the specific needs and preferences of travelers vary from city to city. Achieving positive outcomes relies heavily on the effective transmission of information and the use of modern technologies that make it easier for individuals to transition from private car usage to more sustainable modes of transport, such as public transit, cycling, or car-sharing services. In some cases, individuals may still prefer to use cars, but there is an opportunity to encourage the adoption of cleaner energy vehicles, such as electric or hybrid cars, which have a lower environmental impact. While this option does not reduce car usage per se, it mitigates the harmful effects of conventional vehicle emissions. The key to successful implementation lies in understanding the real needs of travelers. Decision-makers must assess the specific transportation behaviors and requirements of the local population to craft tailored solutions that encourage more eco-friendly choices. This could involve improving public transport accessibility, integrating seamless payment systems like city cards or QR codes, or promoting the use of electric vehicles through incentives. In any case, a combination of well-targeted strategies is necessary to address the unique challenges and opportunities within a given urban area.

The ultimate goal is to create a more sustainable transport system that aligns with both environmental objectives and the practical needs of the community. This focus on understanding and fulfilling the concept of needs is central to one of the most well-known definitions of sustainable development. Addressing the specific transportation needs of urban populations is essential for creating more efficient and sustainable systems. Based on the review of solutions presented by the authors, the next logical step would be to conduct research on the impact of individual transport solutions, such as bike- and car-sharing programs, in addressing issues like traffic congestion and reducing the number of vehicles per household. These forms of shared mobility offer promising alternatives to traditional car ownership, potentially leading to fewer cars on the road and more efficient use of urban space. Overall, the review provided in the text could serve as a valuable resource for both researchers and city authorities. For scientists, it may form the basis for further research on sustainable transport development, offering insights into how different solutions contribute to urban mobility and environmental goals. For city planners and policymakers, it provides a practical reference for considering the integration of new mobility services, such as bike- and car-sharing systems, into their local transport infrastructure. These services could be a vital component in promoting sustainable urban transportation, improving the quality of life for residents while reducing environmental impacts.

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