Research on the Evaluation Indicator System for Sustainable Development of Urban Roads Based on the Triple Bottom Line Theory

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Abstract: This study aims to explore the crucial significance of sustainable development in urban roadways, highlighting its key role in promoting economic growth, social equity, and environmental conservation. Drawing on the Triple Bottom Line theory, which encompasses economic, social, and environmental dimensions, the research analyses the impact of urban road planning, design, and management within these areas. A comprehensive set of sustainability assessment indicators for urban roads is developed using analytic hierarchy process, establishing evaluation criteria across the economic, social, and environmental dimensions. This study proposes a sustainable development model for urban roads and verifies the effectiveness of the Triple Bottom Line theory in the field of sustainable urban road development.

1. Page layout

As global urbanization accelerates, the sustainable development of urban road networks has become a critical issue in city planning and management. Traditional urban road development models have focused too much on accommodating increasing traffic flow and enhancing vehicular efficiency, often overlooking the needs for social equity and environmental protection. The Triple Bottom Line theory offers a comprehensive framework for evaluating the sustainability of urban roads, emphasizing the balance between economic benefits, social responsibility, and environmental impact[1]. This research aims to explore how to apply the TBL theory to the planning and management of urban roads to promote their sustainable development across economic, social, environmental dimensions.

Urban roads are not only a crucial component of city infrastructure but also vital for economic growth, social interaction, and cultural exchange. Research on sustainable urban road development based on the TBL theory requires us to focus not only on the economic benefits of road construction but also on its contributions to social justice and environmental protection. Economically, the study will investigate how to improve cost-effectiveness through sensible design, construction, and maintenance of urban roads, while also fostering economic growth and enhancing the standard of living for residents. Environmentally, the research will examine the potential of urban roads to reduce pollution and greenhouse gas emissions, as well as how green design and construction practices can protect and improve the urban ecological environment. The basic research framework is illustrated in Figure 1.

Fig. 1. Framework for Sustainable Urban Road Development

2. Basic Concepts and Theories

2.1. The Triple Bottom Lines Principle

The Triple Bottom Line is a framework for measuring the success of organizations or projects, emphasizing the importance of economic, environmental, and social dimensions. Sustainable development is about meeting present needs without compromising the ability of future generations to meet their own needs[2]. For urban roads, this means creating a transportation system that supports
city economic growth, reduces environmental impact, and promotes social equity. As part of infrastructure investment, the economic impact of urban roads is mainly reflected in their construction and maintenance costs, as well as their ability to support economic activities. Road planning and management should include long-term cost-benefit analysis to ensure investments yield the greatest economic returns. The social impact of urban roads involves their effect on residents’ quality of life. This includes road safety, support for public transport, enhancement of community connectivity, and accessibility for people with disabilities and pedestrians. The environmental impact of urban roads is primarily seen in their consumption of natural resources, disruption to ecosystems, and effects on air quality. When planning new roads or upgrading existing ones, efforts should be made to minimize damage to the natural environment, such as using eco-friendly materials, reducing emissions and noise pollution. Additionally, encouraging the use of public transport and non-motorized vehicles can help reduce environmental impact. Applying the Triple Bottom Line theory to the management of urban roads means that city planners and managers need to balance these three dimensions' objectives to achieve long-term sustainable development.

2.2. Life Cycle Theory of Urban Roads

The urban road life cycle theory is a framework used to describe and manage the entire process of urban roads from planning and construction, through to usage, maintenance, and eventual decommissioning. This theory treats roads as assets whose effectiveness and value change over time. Urban planners and engineers plan the road's location, size, and design to meet the city's evolving needs, including traffic flow projections, future development expectations, and environmental impact assessments. Construction involves the actual building activities such as land leveling, laying foundations, paving surfaces, installing drainage systems, and establishing signage and traffic lights. The quality of construction directly impacts the road's lifespan and future maintenance costs. Once built, the road enters the operation phase, where it must withstand the daily use by vehicles and pedestrians, leading to wear and tear, damage, and aging. The focus of this phase is to ensure the road's smooth and safe function. Regular maintenance and repair, such as filling potholes, resurfacing damaged roads, cleaning drainage systems, and updating signs, are essential to extend the road's service life, reduce long-term repair costs, and improve service quality. Eventually, when a road no longer effectively meets traffic demands or its maintenance costs become too high, it may be decommissioned[3]. The materials from demolished roads can be repurposed for other uses or recycled, allowing for sustainable urban planning.

3. Construction of urban road evaluation index

3.1. Construction of economic evaluation index of urban roads

The construction of economic evaluation indicators for the full life cycle of urban roads refers to a set of benchmarks that provide a comprehensive assessment of the economic benefits and costs throughout the entire cycle of road planning, design, construction, operation, maintenance, and eventual decommissioning or reconstruction[4]. The economic indicator system for the life cycle of urban roads is composed of four dimensions: initial investment costs, operational costs, maintenance and upgrade costs, and dismantling and regeneration costs. Each dimension's economic indicators are as illustrated in Figures 2. Establishing a full life cycle economic evaluation indicator system aids decision-makers in gaining a more comprehensive understanding of the economic benefits of urban road projects, ensures the scientific and rational nature of project decisions, and promotes the effective allocation of resources and the long-term sustainable management of road assets.

3.2. Construction of economic evaluation index of urban roads

The environmental assessment of the entire life cycle of urban roads is a systematic analytical process aimed at evaluating the environmental impacts at all stages, from construction and usage to demolition and recycling. Establishing an effective set of environmental assessment indicators is crucial for achieving sustainable development and environmental management. When constructing indicators for the environmental evaluation of urban roads' full life cycle, it is necessary to consider resource consumption, emissions and pollution, water pollution, impact on biodiversity, noise pollution, land
use, waste and by-products, and the impact on water resources. By using Life Cycle Assessment (LCA), we can take into account all relevant environmental impacts more comprehensively, thus providing a correct pathway for the sustainable development of urban roads. The system of environmental assessment indicators for urban roads is shown in Fig. 3.

3.3. Construction of Social Evaluation Indicators for Urban Roadways

The construction of a systematic framework aims to comprehensively assess the impact of road systems on various aspects of society, including the economy, environment, social and cultural factors. The urban road social evaluation indicator system covers multiple dimensions to ensure a thorough assessment of the impact of city roads on residents' quality of life, economic activities, the environment, and social welfare. Such an evaluation system aids decision-makers in road design, construction, and management to maximize social benefits. When establishing an urban road social evaluation indicator system, it's crucial to ensure the indicators are scientific, systematic, applicable, and comparable. It's also important to consider the interrelationships and trade-offs between indicators, and how to quantify them through data collection and analysis. The selection of indicators should accurately reflect the social impact of urban roads, and the data should be feasibly obtainable. The social evaluation indicator system should be adaptable to adjust according to the specific circumstances and needs of different cities. This provides strong decision-making support for the planning, construction, and management of urban roads, promoting the sustainable development of road systems. Each dimension's Social Evaluation indicators are as illustrated in Figures 4 and Figures 5.

The Urban Road Social Evaluation Index System is a comprehensive analytical framework designed to assess the impact of urban road networks on various aspects of society. This system typically encompasses multiple dimensions, including transportation efficiency, safety, environmental impact, social equity and accessibility, economic effects, society cultural aspects, user satisfaction, and policy and planning. Transportation efficiency metrics evaluate road congestion levels, travel speed, and the effectiveness of public transport. Safety metrics focus on the incidence and consequences of road traffic accidents and the adequacy of safety facilities. Environmental impact metrics take into account the effects of road traffic on air quality, noise pollution, and natural ecosystems. Social equity and accessibility metrics ensure that different social groups have equal access to transportation services. Economic impact metrics assess the costs of road construction and maintenance, as well as the impact of traffic delays on the economy. Plays a critical role by providing policymakers, urban planners, and traffic managers with a comprehensive tool to assess the social impact of urban transport networks. This system allows for the quantification and monitoring of urban roads' overall performance in terms of traffic efficiency, safety, environmental quality, social equity, economic development, cultural aspects, and user satisfaction. These indicators assist decision-makers in identifying areas of concern, optimizing resource allocation, and formulating effective strategies to enhance road performance, reduce traffic congestion and accidents, and lower environmental pollution. They ensure the fairness and accessibility of the transport system for all users. Ultimately, the system enhances public participation by incorporating resident feedback to improve road planning and services. Ultimately, this framework promotes the sustainable development of urban road networks, improves residents' quality of life, and contributes to the city's long-term development goals.
4. Strategies and Suggestions for Sustainable Development of Urban Roads

In order to evaluate the sustainable development of urban roads, a comprehensive set of indicators has been established. Taking into account the entire lifespan of urban roads, strategies and recommendations for sustainable development are proposed from the perspectives of economy, environment, and society. From an economic sustainability standpoint, the primary focus is on ensuring the efficiency and effectiveness of road investments. In terms of environmental sustainability, the construction and operation of urban roads should aim to minimize negative environmental impacts and promote environmental protection and improvement. From a social sustainability perspective, the focus is on how the road system can meet social needs, promote social justice, and enhance quality of life.

4.1. Sustainable Development Strategies in the Economic Dimension

The economic sustainability of urban roads first requires ensuring the efficiency and effectiveness of investments. The cost of road construction and maintenance must be justified by increased traffic flow and reduced congestion. Economic indicators such as road usage, toll revenue, operating costs, and capital return rate should be used to assess whether the road has maximized cost-effectiveness. Diverse funding sources for road construction, including private investment, public-private partnerships (PPP), and other innovative financing mechanisms, should be considered to reduce the government's financial burden. This financial structure helps to spread risks while ensuring sustained investment and efficient operation of road projects. The economic sustainability of urban roads should also consider their role in promoting other economic activities in the city. The road network should connect with the city's commercial, industrial, and residential areas to stimulate economic growth and employment opportunities. Evaluation indicators should include measures of the road's impact on the local economy, such as employment growth rate, business activity growth, and regional output increase. Maintenance and upgrades of urban roads are also crucial for economic sustainability. Regular road maintenance can reduce long-term repair costs, extend the road's lifespan, and maintain its performance. Efficiency indicators in the evaluation system, including maintenance costs, repair time, and road condition ratings, should be used to monitor the economic efficiency of road maintenance.

4.2. Sustainable Development Strategies for Environmental Dimension

From a sustainability perspective, the construction and operation of urban roads should focus on reducing evaluation indicators such as greenhouse gas emissions from road traffic and air quality index to monitor the impact of roads on the environment. To improve energy efficiency, the lighting and signal systems of urban roads should adopt energy-saving technologies, such as LED lighting and intelligent traffic management systems, to reduce energy consumption. Strengthening ecological protection and greening, ecological corridors and green spaces should be considered in road planning and design to maintain biodiversity. Indicators such as vegetation coverage and ecological corridor connectivity can be used to evaluate the environmental friendliness of urban roads. To reduce noise pollution, use sound barriers, road noise absorption materials, and restrict high-noise vehicles to reduce noise impact on surrounding residents and wildlife. Strengthening rainwater management and reducing runoff pollution: through the construction of permeable road surfaces, rain gardens, and other green infrastructure, urban roads should promote natural infiltration and purification of rainwater, reducing runoff pollution of water bodies.

4.3. Sustainable Development Strategies in a Social Context

The social sustainability of urban roads focuses on how the road system meets societal needs, promotes social justice, and enhances quality of life. This includes providing accessible facilities for people with disabilities and good public transport connections for low-income communities. Enhancing safety, road design should aim to reduce traffic accidents and improve the safety of pedestrians, cyclists, and vehicle passengers. This can be achieved by reducing traffic conflict points, establishing safe pedestrian crossings and bike lanes, and implementing effective traffic regulations and supervision measures. Increasing community connectivity and cohesion, urban road design should
promote connectivity between communities, avoiding the formation of isolated "road barriers". By incorporating greenery, public spaces, and pedestrian-friendly streets, roads can become places for community interaction, enhancing community cohesion[5].

5. Conclusion

Overall, the economic sustainability of urban roads requires a comprehensive evaluation and monitoring system to ensure cost-effective road construction and maintenance, diverse fund-raising, positive impact on other economic activities in the city, and efficient road maintenance management. The environmental sustainability of urban roads needs to be monitored and managed through a comprehensive set of evaluation indicators, including reducing greenhouse gas emissions, improving energy efficiency, protecting ecosystems, controlling noise pollution, managing storm water runoff, and using sustainable materials. The social sustainability of urban roads is crucial to ensuring long-term benefits for society. By improving accessibility, safety, community connectivity, economic opportunities, and public health, and raising public awareness through education and promotion, urban roads can promote a more inclusive, healthy, and cohesive society.

References