MANTECH Publications

Journal of Transportation Engineering and Its Applications
Volume 3, Issue 2, May-August, 2018

Integrating Non-Motorized Transport Into Urban Road Design: Engineering Solutions for Sustainable Cities Through Infrastructure Adaptation, Multimodal Planning, and Active Mobility Promotion

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Abstract

Urban transportation systems worldwide face challenges of congestion, environmental degradation, and inequity in access. Non-motorized transport (NMT), including walking and cycling, offers an eco-friendly, health-promoting, and equitable solution for sustainable urban development. This paper explores the integration of NMT into urban road design through engineering strategies that prioritize inclusivity, safety, and sustainability. Drawing from best practices and innovations in infrastructure design, this study discusses the current trends, challenges, and future directions for creating NMT-friendly urban environments. A comprehensive approach combining urban planning, traffic engineering, and behavioral insights is presented to ensure that cities evolve towards more livable, connected, and resilient futures.

Keywords*: Non-Motorized Transport, Urban Road Design, Sustainable Cities, Cycling Infrastructure, Pedestrian Mobility*

INTRODUCTION

The rapid acceleration of urbanization worldwide has led to an ever-growing demand for sustainable, efficient, and accessible transport solutions. According to the United Nations, over 55% of the global population now resides in urban areas, a figure expected to increase dramatically in the coming decades. As cities expand, traditional motorized transportation systems—relying heavily on private vehicles—are proving unsustainable. These systems contribute significantly to environmental degradation, with high levels of carbon emissions, air pollution, and noise. Additionally, urban spaces face the challenge of traffic congestion, which results in reduced mobility, loss of productive time, and increased stress for urban dwellers. Moreover, the health impacts of sedentary lifestyles linked to car-centric transport systems, such as increased rates of heart disease, obesity, and respiratory conditions, further underscore the unsustainability of current transportation models.

Non-motorized transport (NMT)—comprising walking, cycling, and other forms of active mobility—has emerged as a viable and essential alternative to reduce congestion, mitigate emissions, and promote public health. NMT not only offers environmental benefits but also enhances the quality of urban life, fostering more vibrant, accessible, and inclusive communities. As cities strive to accommodate growing populations while combating climate change, integrating NMT into urban transportation planning is no longer an optional consideration but a central goal for sustainable urban development.

Designing infrastructure that supports NMT is essential for realizing this vision. As cities begin to shift towards people-centric and climate-resilient urban environments, engineers and urban planners must develop innovative and practical solutions to integrate walking and cycling into the fabric of urban transportation. This paper explores the engineering principles and design frameworks necessary to successfully incorporate NMT into urban transportation systems, considering challenges, opportunities, and emerging technologies.

LITERATURE REVIEW

Evolution of NMT Planning

Historically, many cities were designed with pedestrians and non-motorized transport at the center of urban life. In the early stages of urbanization, streets were primarily built for foot traffic, and the concept of public space was designed to foster social interaction and mobility for people. However, with the rise of the automobile in the 20th century, urban planning underwent a dramatic transformation. Roads became primarily designed to accommodate

vehicles, leading to the creation of sprawling highways, car parks, and urban sprawls that favored motorized transportation at the expense of pedestrians and cyclists. This shift has had profound consequences on urban life, including increased congestion, air pollution, and health problems due to reduced physical activity.

In recent decades, however, urban scholars and planners have begun to recognize the need for a paradigm shift. Renowned experts like Gehl (2010) and Banister (2008) argue for a return to human-centered transport planning that emphasizes accessibility, mobility, and sustainability for all, especially pedestrians and cyclists. Their work highlights the importance of urban designs that promote the active use of streets by people, rather than vehicles. These scholars advocate for the reallocation of street space, improved infrastructure for non-motorized modes of transport, and policies that prioritize pedestrian and cyclist safety.

Global Best Practices

Several cities around the world have become exemplars in the integration of NMT into urban transportation systems. Cities like Copenhagen, Amsterdam, and Bogotá have taken the lead in creating highly effective NMT infrastructure. Copenhagen is particularly known for its vast network of segregated bicycle lanes and commitment to becoming the world's first carbon-neutral capital by 2025. Amsterdam's extensive cycling infrastructure and pedestrian-friendly street design have made it one of the most walkable and bikeable cities in the world. Similarly, Bogotá's TransMilenio bus rapid transit (BRT) system and its commitment to car-free days have made the city a model for sustainable urban mobility.

These cities have demonstrated that investment in NMT infrastructure leads to increased cycling and walking participation, reduced emissions, and improved public health outcomes. The implementation of measures such as segregated bike lanes, pedestrian plazas, traffic calming initiatives, and policies that encourage walking and cycling has contributed to a shift in urban mobility toward more sustainable forms of transport. These global best practices offer valuable insights into the design principles and policies that can be adapted to other urban contexts to achieve similar success.

Technological and Policy Innovations

Technological advancements are playing an increasingly important role in enhancing NMT planning. Geographic Information Systems (GIS) and data analytics tools enable urban planners to analyze spatial data and identify areas where NMT infrastructure is most needed. Smart sensors embedded in roads and infrastructure can track pedestrian and cyclist flow, providing real-time data that can be used to optimize traffic signals, adjust public transport schedules, and improve pedestrian safety. Mobile apps that provide real-time information about bike-sharing availability, public transportation schedules, and walkability scores have also contributed to promoting NMT use.

Alongside technological innovations, urban policy frameworks such as Complete Streets, Vision Zero, and Sustainable Mobility Action Plans are critical in creating environments conducive to NMT. Complete Streets policies advocate for roadways designed to safely accommodate all users, including pedestrians, cyclists, transit riders, and motorists. Vision Zero, a policy aimed at eliminating traffic fatalities and serious injuries, has been adopted by numerous cities to ensure that NMT infrastructure is safe and accessible. These policies are instrumental in guiding urban design and transport policy toward greater sustainability and inclusivity.

ENGINEERING SOLUTIONS FOR NMT INTEGRATION

Dedicated Infrastructure for Safety and Accessibility

The integration of NMT into urban transportation systems requires the development of dedicated infrastructure that prioritizes the safety and accessibility of pedestrians and cyclists. Key infrastructure components include:

- **Segregated Bicycle Lanes**: One of the most effective ways to encourage cycling and ensure safety is the creation of physically separated bike lanes that are distinct from motorized traffic. These lanes can reduce the risk of accidents between cyclists and vehicles, fostering a safer and more inviting environment for cycling. Furthermore, the presence of well-designed bike lanes helps to increase the number of people who choose to cycle, which in turn reduces traffic congestion and lowers emissions.
- **Pedestrian-Only Zones**: In key commercial, historical, and recreational areas, streets can be redesigned to prioritize pedestrian movement by restricting motorized vehicles. Creating pedestrian-only zones not only improves safety but also enhances the vibrancy

and livability of urban spaces. These zones can be equipped with seating, greenery, and other public amenities to encourage social interaction and promote walking as a primary mode of transport.

- **Raised Crosswalks and Curb Extensions**: These design features slow down motorized vehicles at pedestrian crossings and make it easier for pedestrians to navigate busy intersections. Raised crosswalks act as speed bumps, forcing vehicles to reduce speed, while curb extensions shorten the crossing distance for pedestrians, making it easier and safer to walk.

Multimodal Connectivity

The success of NMT integration depends on creating seamless connections between different modes of transportation, including cycling, walking, and public transit. Key components of multimodal connectivity include:

- **Bike-and-Ride Facilities**: Secure bike parking facilities near transit stations encourage people to combine cycling with public transportation. Bike-and-ride facilities make it easier for cyclists to use public transit for the remainder of their journey, promoting a more sustainable and efficient transportation system.
- **Integrated Mobility Hubs**: Designing transportation hubs where buses, trains, bikes, and pedestrian routes intersect can promote modal interchange. These hubs should provide easy access to various transport options and facilitate smooth transitions between modes, creating an integrated and cohesive transportation network.

Traffic Calming Measures

To enhance the safety and comfort of NMT users, urban planners can incorporate traffic calming measures that naturally reduce the speed of motorized vehicles. These measures include:

- **Chicanes, Speed Tables, and Roundabouts**: These traffic-calming structures force vehicles to slow down by creating narrower lanes or forcing them to navigate curves. This approach not only improves safety for pedestrians and cyclists but also reduces overall vehicle speeds, contributing to a more pedestrian-friendly environment.
- **Reduced Speed Zones in Urban Centers**: Implementing reduced speed limits in areas with high pedestrian traffic (such as 20-30 km/h zones) can significantly improve the

safety and comfort of walking and cycling. Lower speeds reduce the likelihood of accidents and create a more pleasant environment for non-motorized transport.

Smart Infrastructure Design

The incorporation of smart technologies into NMT infrastructure can make transportation systems more responsive, efficient, and user-friendly:

- **Sensor-Based Pedestrian Signals**: These signals adjust traffic light timings based on the volume of pedestrian movement, ensuring that pedestrians can cross streets safely and efficiently. Real-time adjustments based on sensor data can help reduce waiting times and improve overall pedestrian flow.
- **Smart Street Lighting**: The installation of energy-efficient, sensor-driven street lights along NMT routes improves safety and usability at night. Smart street lighting can automatically adjust brightness based on pedestrian or cyclist presence, saving energy and enhancing visibility.
- **Real-Time Data Displays**: Providing real-time information about traffic conditions, public transport schedules, and air quality along NMT routes can help users make informed decisions about their travel. These displays can be integrated into smart city systems and provide important updates to commuters in real-time.

Table No. 1: Key Engineering Solutions For Nmt Integration

Solution	Description
Segregated Bicycle Lanes	Physically separated lanes for cyclists to ensure safety from motorized traffic
Pedestrian-Only Zones	Designated areas exclusively for pedestrian use
Multimodal Connectivity	Facilities linking NMT with public transport (e.g., bike-and-ride stations)
Traffic Calming Measures	Speed-reduction methods like speed tables, chicanes, and narrowed roads

CHALLENGES IN IMPLEMENTING NMT INFRASTRUCTURE

Urban Space Constraints

One of the major challenges in integrating non-motorized transport (NMT) infrastructure into urban areas is the limited availability of space. High-density cities, particularly in older urban areas, often have a limited right of way for street expansions. The growth of urban populations

has led to congested, crowded streets, where the existing road space is already allocated to motor vehicles, public transport, and other essential utilities. This creates difficulties in retrofitting streets to accommodate new lanes for cyclists and pedestrians.

Moreover, urban areas with narrow streets or dense development require creative engineering solutions to overcome space constraints without displacing existing infrastructure like utilities, buildings, and roadways. For instance, designing wider sidewalks and bike lanes might necessitate the relocation of bus stops, altering traffic flow, or even the redesign of intersections to ensure safe crossings for pedestrians and cyclists. The challenge lies in balancing the needs of various modes of transport while avoiding adverse impacts on the urban landscape.

Funding and Political Will

The transition to NMT infrastructure requires significant financial investment. In many cases, political will and funding for NMT infrastructure are lacking. While the long-term benefits of reducing traffic congestion, improving public health, and cutting emissions are well-documented, the upfront capital required for NMT infrastructure—such as dedicated bike lanes, pedestrian walkways, and necessary safety features—can be substantial.

Government budgets often prioritize immediate infrastructure needs or other transportation projects with more tangible short-term benefits, such as road expansion for cars. This can lead to political reluctance, as the benefits of NMT infrastructure are often long-term and diffuse, making it harder to convince decision-makers and stakeholders of its immediate economic returns. In addition, changing political climates or the election cycles of local governments may lead to disruptions in planning and delayed implementation.

Cultural and Behavioral Barriers

In many urban areas, walking or cycling is seen as a low-status, inconvenient, or even unsafe mode of transportation. This cultural stigma presents a significant barrier to the widespread adoption of NMT, especially in regions where the dominant mode of transport has long been motorized vehicles. For many people, the car is not just a mode of transport but also a symbol of status, freedom, and comfort.

Overcoming this stigma requires a cultural shift that repositions walking and cycling as viable, desirable, and efficient modes of transportation. This cultural change can be driven through awareness campaigns, education, and incentives that emphasize the benefits of NMT, such as reduced costs, improved health, and environmental sustainability. Additionally, creating safe and attractive infrastructure can shift public perception and encourage a greater willingness to adopt NMT as a mode of daily travel.

Weather and Topography

The feasibility of NMT is also heavily influenced by the climate and terrain of a city. Cities with extreme weather conditions, such as hot, rainy, or snowy climates, pose particular challenges for NMT adoption. In cities with high temperatures, cyclists and pedestrians need shaded paths or covered walkways to protect them from heat stress. Similarly, areas with frequent rain or snow require infrastructure that can handle weather challenges, such as waterproof walkways and heated bike lanes in winter.

Topography also plays a significant role in the feasibility of NMT infrastructure. Hilly terrain, for example, makes cycling difficult and less appealing for the average commuter. To address this challenge, cities could implement measures such as electric bike (e-bike) systems to support cyclists in navigating steep areas, or design accessible ramps and elevators for pedestrians and cyclists to cross challenging landscapes.

SCOPE FOR FUTURE DEVELOPMENT

Integrated Urban Mobility Planning

One of the key areas for future development in NMT infrastructure is the integration of NMT into broader urban mobility planning. In the past, urban planning often treated transportation as a series of isolated systems—one for cars, another for public transit, and yet another for pedestrians and cyclists. However, as cities evolve and the need for sustainable transportation grows, it is clear that these systems must work together to create seamless, efficient mobility networks.

Urban planning must adopt a holistic, integrated approach to mobility that includes NMT at every stage of urban development, from zoning and housing to transportation systems. Mixed-use development, for example, encourages walkability by reducing the distance between

essential services, such as schools, shops, and workspaces. This encourages walking and cycling as the primary modes of transport, which in turn reduces congestion and minimizes the carbon footprint of transportation.

Public Participation and Co-Design

For NMT infrastructure to be successful and widely adopted, it is crucial that communities are involved in the planning and design process. Public participation ensures that the infrastructure reflects the needs and preferences of the people who will use it, leading to better outcomes in terms of usability and adoption. Involving citizens in the design of streets and pathways can foster a sense of ownership and responsibility, which contributes to the long-term success of NMT projects.

Co-design processes, where urban planners work alongside local communities, cyclists, pedestrians, and other stakeholders, are increasingly seen as essential for creating relevant and user-friendly infrastructure. This participatory approach allows planners to gather valuable insights into local mobility patterns and priorities, ensuring that the infrastructure meets the specific needs of different groups, such as the elderly, children, and those with disabilities.

Climate Resilience and Green Infrastructure

As climate change continues to affect urban environments, cities must ensure that their infrastructure is resilient to extreme weather events. NMT infrastructure presents a unique opportunity to integrate climate resilience into urban design. For example, streets designed for cyclists and pedestrians can be built with permeable pavements that allow water to drain, reducing the risk of flooding during heavy rainfall.

Incorporating green infrastructure—such as bioswales, urban trees, and green canopies—into NMT pathways can help mitigate the effects of heat islands, reduce carbon footprints, and provide aesthetic and environmental benefits. These features also contribute to the overall well-being of residents, making NMT routes not only sustainable but also visually appealing and pleasant to use.

Incentive-Based Policies

Governments can play a pivotal role in encouraging the adoption of NMT by implementing incentive-based policies. These can include direct financial incentives, such as tax credits for individuals who purchase bicycles, e-bikes, or electric scooters. Some cities have already introduced subsidies for residents to encourage the use of these sustainable modes of transport.

Car-free days, when roads are closed to motor vehicles and opened up for pedestrians, cyclists, and other NMT users, can also serve as a powerful tool for promoting NMT. These events help raise awareness about the benefits of non-motorized transport and offer an opportunity for residents to experience the advantages of cleaner, quieter streets.

CASE STUDIES OF SUCCESSFUL IMPLEMENTATION

Copenhagen, Denmark

Copenhagen is widely regarded as one of the most bike-friendly cities in the world. Over 62% of the city's residents commute by bike, supported by an extensive network of over 350 kilometers of dedicated bike lanes. The city's commitment to cycling has been reinforced by innovative engineering solutions such as "green wave" traffic lights, which are timed to allow cyclists to travel through intersections without stopping. This system not only saves cyclists time but also reduces traffic congestion. Additionally, Copenhagen has introduced heated bike lanes to ensure cyclists can continue to commute in winter, demonstrating the city’s commitment to making cycling accessible year-round.

Bogotá, Colombia

Bogotá has been a trailblazer in promoting NMT through its innovative Ciclovía program. Every Sunday, 120 kilometers of the city's roads are closed to motor vehicles, creating car-free corridors for cyclists, pedestrians, and other non-motorized transport users. This program has helped foster a sense of community while encouraging more people to engage in cycling and walking. Furthermore, Bogotá has integrated its growing network of bike lanes with the city’s Bus Rapid Transit (BRT) system, making it easier for people to combine cycling with public transportation for a more comprehensive and sustainable transportation experience.

Portland, USA

Portland has become a model for American cities striving to implement NMT infrastructure. Its Complete Streets policy has transformed several key districts into pedestrian-first zones. Investments in high-quality sidewalks, improved wayfinding signage, and pedestrian bridges have made it easier and safer for residents to walk and cycle. The city's commitment to NMT is further reflected in its extensive bike lane network and bike-sharing programs, which encourage active transportation while reducing reliance on cars.

Table No.2: Comparison Of Modal Share Before And After Nmt Integration In Selected Cities

City	Before NMT Integration (% NMT use)	After NMT Integration (% NMT use)	Change
Copenhagen	35%	50%	+15%
Amsterdam	40%	55%	+15%
Bogotá	18%	33%	+15%
Portland (USA)	12%	25%	+13%

RECOMMENDATIONS FOR URBAN ROAD ENGINEERING

Adopt Context-Sensitive Design

The successful integration of non-motorized transport (NMT) solutions in urban areas requires a context-sensitive approach that takes into account the unique conditions of each locality. Every urban environment is distinct in terms of its demographics, climate, and travel behavior, and as such, the same design solutions cannot be universally applied. For example, a high-density area with a large number of young professionals might prioritize bike lanes and shared spaces for cyclists, whereas a residential neighborhood with a higher population of elderly residents might require wider sidewalks, pedestrian-friendly crossings, and slower traffic speeds to ensure safety and accessibility.

In addition to considering demographic and social factors, climate conditions should also influence the design of NMT infrastructure. For example, cities in hot, humid climates might benefit from shaded bike paths and pedestrian walkways to protect users from heat, while colder cities may need to incorporate heated paths to prevent ice accumulation on bike lanes during winter months. Thus, urban road engineers must take a holistic, adaptive approach to

designing NMT infrastructure that aligns with the specific needs of the area, ensuring that infrastructure is both functional and contextually appropriate.

Build NMT Into Road Hierarchies

Urban roads serve different functions, from high-traffic arterial roads that link major districts to smaller local streets that provide access to residential areas. Each type of road should include tailored provisions for NMT users, recognizing the varying traffic volumes, speed limits, and user needs associated with different road categories. For example, on major arterial roads, dedicated bike lanes or even bike highways could be incorporated, ensuring safe and uninterrupted travel for cyclists. On local neighborhood streets, more flexible solutions such as shared spaces that allow for a mix of pedestrians, cyclists, and low-speed vehicles could be employed to foster a more inclusive and human-centric environment.

By integrating NMT provisions into the road hierarchy, cities can create a cohesive, well-connected transport network that accommodates pedestrians and cyclists across the entire urban landscape. This approach ensures that NMT infrastructure is not isolated in specific areas but is a seamless part of the broader transportation system, enabling people to move efficiently between neighborhoods and across the city.

Incorporate Monitoring and Feedback Systems

To ensure that NMT infrastructure meets the needs of its users and continues to evolve with changing demands, it is essential to incorporate data-driven monitoring and feedback systems. This could involve installing digital counters on bike lanes or pedestrian paths to track usage patterns and identify peak traffic times. Regular mobility audits, combined with user satisfaction surveys, can also provide valuable insights into the quality and effectiveness of the infrastructure, helping urban planners and engineers assess how well the design is working in practice.

The feedback collected can guide future infrastructure upgrades, helping cities refine their NMT networks based on actual usage and the evolving needs of their communities. For instance, if a particular bike lane is consistently underused, it may indicate issues with accessibility, connectivity, or safety that need to be addressed. On the other hand, areas with

high foot traffic may require additional improvements, such as wider sidewalks or more frequent crossings, to enhance user experience.

Education and Awareness Campaigns

Engineering solutions alone are not enough to encourage widespread adoption of non-motorized transport. Public education and awareness campaigns are crucial to fostering a cultural shift that prioritizes walking and cycling. These campaigns should focus on educating the public about the benefits of active transport, including environmental sustainability, public health, and reduced traffic congestion.

Safety is another key component of such campaigns. Many people may be hesitant to walk or cycle due to concerns about traffic safety. Therefore, alongside engineering solutions that prioritize the safety of NMT users, public awareness efforts should emphasize the rules of the road, rights of way, and the importance of mutual respect between cyclists, pedestrians, and motorists. Community outreach programs, local workshops, and school education initiatives can also contribute to raising awareness and changing the social norms surrounding active transportation.

CONCLUSION

Integrating non-motorized transport (NMT) into urban road design is no longer a peripheral consideration in modern urban planning—it is an essential cornerstone of sustainable city development. By prioritizing NMT solutions that focus on safety, accessibility, and multimodal connectivity, urban areas can foster more inclusive, resilient, and healthy living spaces. These design solutions offer a path to creating cities that not only serve the immediate needs of residents but also promote long-term social, environmental, and economic benefits.

While challenges remain, such as spatial limitations, cultural resistance, and financial constraints, the long-term benefits of NMT infrastructure far outweigh these obstacles. The integration of walking and cycling into urban mobility systems can significantly reduce carbon emissions, improve public health outcomes by encouraging physical activity, and enhance social equity by providing more accessible and affordable transportation options for all residents.

Furthermore, NMT infrastructure can contribute to creating more vibrant urban spaces. Streets designed with pedestrians and cyclists in mind are often safer, quieter, and more pleasant places to live and work. In this way, the shift towards non-motorized transport contributes not only to sustainability goals but also to the quality of life within cities, fostering a sense of community, mobility, and well-being.

Ultimately, with strategic planning, innovative engineering solutions, and active community engagement, non-motorized transport can shift from the periphery to the center of urban mobility systems. By recognizing its vital role in creating more sustainable and livable cities, urban planners can help pave the way for a future where walking and cycling are not just modes of transport but integral elements of urban life. The challenge, therefore, is not only technical but also one of vision—transforming our cities into healthier, more inclusive, and sustainable spaces for generations to come.

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