

# Integrating Smart Geotechnical Systems and Sustainable Urban Mobility for Parking and Pedestrian Infrastructure in Congested Old Indian Cities

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**Abstract:** This study integrates sustainable mobility planning with intelligent geotechnical engineering to address the challenges of parking and pedestrian management in congested old Indian cities. Traditional mobility solutions often overlook the subsurface dimension, foundation stability, ground movement, and soil-structure interaction that critically influence urban infrastructure durability. Author proposes a hybrid framework combining smart parking technologies, pedestrian-friendly designs, and intelligent geotechnical monitoring systems. Real-time data from embedded sensors, including strain gauges, fiber-optic cables, and piezometers can provide predictive insights into foundation settlement beneath multi-level parking structures and pedestrian zones. Artificial intelligence and data analytics can further optimize maintenance, minimize risk, and enhance safety in heritage areas with aging underground utilities. The integration of surface mobility planning with subsurface geotechnical intelligence creates a holistic approach to sustainable, resilient, and data-driven urban infrastructure for rapidly urbanizing old Indian cities.

**Keywords:** Intelligent geotechnical systems, Smart parking, Pedestrian infrastructure, Soil-Structure interaction, AI in urban planning, Sustainable mobility.

## 1. INTRODUCTION

India is a land of vibrant culture, rich history, and bustling cities. Its ancient urban centers bear witness to centuries of growth and development, each layer of history adding to the complexity of its urban fabric. However, with progress comes challenges, and perhaps none are as pressing in contemporary India as those related to urban congestion and mobility. Among the most significant concerns are parking management and pedestrian infrastructure, particularly in the older, densely populated areas of Indian cities. The rapid pace of urbanization and economic development in India have led to unprecedented levels of vehicular traffic in urban centers. According to the World Bank, India is home to some of the most congested cities in the world, with traffic congestion costing the economy of billions of dollars annually [1-3]. The problem is particularly acute in older cities with narrow streets and limited space for parking and pedestrian movement. In these areas, the competing demands of vehicular traffic, pedestrians, and commercial activities often lead to chaos and inefficiency. The issue of parking management is multifaceted. Not only there is a growing demand for parking spaces due to the increasing number of vehicles on the road but also the limited availability of land in congested urban areas makes it challenging to create new parking facilities. As a result, illegal parking on streets and sidewalks is rampant, further exacerbating congestion and posing

safety hazards for pedestrians [4, 5]. Similarly, pedestrian infrastructure in old Indian cities is often inadequate and poorly maintained. Sidewalks are narrow, uneven, and cluttered with obstacles, making it difficult for pedestrians to walk safely and comfortably. Moreover, the lack of designated pedestrian crossings and the encroachment of vehicles onto sidewalks further diminish the pedestrian experience and increase the risk of accidents. Addressing the challenges of parking and pedestrian management in congested old Indian cities requires a comprehensive and sustainable approach. Traditional solutions such as building more roads and parking lots are no longer viable due to space constraints and environmental concerns. Instead, innovative strategies that prioritize the efficient use of existing infrastructure and promote sustainable modes of transport are needed [6-9]. One promising approach is the implementation of smart parking technologies that leverage data and analytics to optimize parking usage and reduce congestion. These technologies, such as dynamic pricing, real-time availability tracking, and mobile parking apps, help drivers find parking spaces more efficiently and discourage illegal parking. Moreover, by reducing the time spent circling for parking, smart parking solutions can lower carbon emissions and improve air quality in urban areas. In addition to technological solutions, there is a growing recognition of the need to prioritize pedestrians in urban planning and design. This includes investing in wider sidewalks, pedestrian-only zones, and well-designed street furniture to enhance the pedestrian experience. Furthermore, integrating green spaces and trees into urban streetscapes not only improves aesthetics but also provides shade and improves air quality, creating a more pleasant and

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sustainable urban environment. Furthermore, promoting alternative modes of transport such as walking, cycling, and public transit is essential for reducing reliance on private vehicles and alleviating congestion. Investing in safe and accessible cycling infrastructure, expanding public transit networks, and implementing measures such as congestion pricing can encourage modal shifts and reduce the demand for parking in urban areas. In conclusion, the challenges of parking and pedestrian management in congested old Indian cities are complex but not insurmountable. By embracing innovative technologies, prioritizing pedestrians, and promoting sustainable modes of transport, cities can create more livable, efficient, and environmentally friendly urban environments [10-13]. This research article aims to explore these issues in depth and propose practical solutions to address them, ultimately contributing to the development of more sustainable and resilient cities in India and other developing countries.

### **1.1. Scope**

The scope of this study encompasses an in-depth examination of parking and pedestrian management issues in congested old Indian cities. It will analyze the current challenges and trends related to parking availability, illegal parking, and pedestrian infrastructure. The study explores the innovative technologies and sustainable strategies for parking management, including smart parking solutions and dynamic pricing mechanisms. Additionally, it investigates urban planning and design interventions aimed at improving pedestrian safety and comfort, such as wider sidewalks, pedestrian-only zones, and green spaces. The research also examines the potential impacts of promoting alternative modes of transport on parking demand and urban mobility patterns. Through comprehensive analysis and empirical evidence, the study aims to provide insights and recommendations for policymakers, urban planners, and stakeholders to address these pressing issues and create more livable and sustainable urban environments.

## **2. STRATEGIES**

### **2.1. Implementation of Smart Parking Technologies**

In the quest for sustainable solutions to parking management in congested old Indian cities, the implementation of smart parking technologies stands out as a promising strategy. Smart parking technologies encompass a range of innovative tools and approaches that leverage data, analytics, and connectivity to optimize parking usage, reduce congestion, and enhance the overall urban mobility experience.

One key component of smart parking technologies is real-time parking availability tracking. Through the deployment of sensors embedded in parking spaces or utilizing existing infrastructure such as CCTV cameras, cities can collect data on parking occupancy in real time. This information is then made available to drivers through mobile apps or digital signage, allowing them to identify vacant parking spaces quickly and efficiently. By reducing the searching time for parking, real-time availability tracking helps alleviate congestion and minimize carbon emissions associated with idling vehicles [14, 15]. Dynamic pricing is another essential feature of smart parking technologies. Instead of fixed parking rates, dynamic pricing adjusts parking fees based on demand, time of day, and other factors. For example, parking rates may be higher during peak hours or in high-demand areas, incentivizing drivers to consider alternative modes of transport or park in less congested areas. By managing parking demand through price signals, dynamic pricing helps optimize the utilization of existing parking infrastructure and reduce the need for additional parking spaces [16].

Mobile parking apps are increasingly popular tools that provide drivers with a convenient way to find, reserve, and pay for parking spaces using their smartphones. These apps typically offer features such as real-time availability tracking, navigation to the nearest parking facility, and cashless payment options. By streamlining the parking experience and reducing friction points such as searching for coins or waiting in line at parking meters, mobile parking apps encourage more efficient use of parking spaces and enhance the overall urban mobility experience. Moreover, smart parking technologies enable cities to collect valuable data on parking usage, traffic patterns, and travel behavior. By analyzing this data, urban planners and policymakers can gain insights into parking demand, identify areas of congestion, and develop targeted interventions to improve traffic flow and reduce emissions [17-19]. For example, data analytics can make decisions on allocation of new parking facilities, designing the parking zones, and implementing demand-based pricing strategies. In addition to optimizing parking usage, smart parking technologies can also contribute to the development of more sustainable and equitable transportation systems. By integrating parking information with other modes of transport such as public transit, cycling, and ride-sharing services, cities can encourage multimodal travel and reduce reliance on private vehicles. For example, mobile parking apps may provide information on nearby public transit routes and schedules, making it easier for drivers to combine driving with other modes of transport for their daily commute.

In conclusion, implementation of smart parking technologies holds great promise for addressing the challenges of parking management in congested old Indian cities. By leveraging real-time data, dynamic pricing, and mobile connectivity, cities can optimize parking usage, reduce congestion, and enhance the overall urban mobility experience. Moreover, smart parking technologies provide valuable insights into parking demand, traffic patterns, and travel behavior, enabling cities to develop more sustainable and equitable transportation systems for the future.

## **2.2. Prioritizing Pedestrians through Urban Design and Infrastructure Enhancement**

In cities, where narrow streets and limited space pose significant challenges to pedestrian movement, prioritizing pedestrians through urban design and infrastructure enhancement are crucial for creating safer, more accessible, and livable urban environment. This strategy involves a holistic approach that encompasses various interventions aimed at improving pedestrian infrastructure, enhancing walkability, and reclaiming public space for pedestrians.

One key aspect of prioritizing pedestrians is investing in wider sidewalks and pedestrian-only zones. In many old Indian cities, sidewalks are narrow, uneven, and cluttered with obstacles, making it difficult for pedestrians to walk safely and comfortably. By widening sidewalks and removing encroachments such as street vendors and parked vehicles, cities can create more space for pedestrians and improve the overall pedestrian experience. Pedestrian-only zones, where vehicular traffic is restricted or prohibited altogether, further enhance walkability and create vibrant, pedestrian-friendly urban spaces. Furthermore, enhancing the quality of pedestrian infrastructure is essential for promoting walking as a sustainable mode of transport. This includes ensuring smooth and level walking surfaces, installing adequate lighting and signage, and providing amenities such as benches, bike racks, and drinking fountains. By making walking more convenient, comfortable, and enjoyable, cities can encourage more people to choose walking for short trips, reducing congestion and pollution caused by motorized transport [20-23]. Another important aspect of prioritizing pedestrians is improving pedestrian safety through traffic calming measures and designated crossing points. Traffic calming measures such as speed humps, raised crosswalks, and narrowed streets help reduce vehicle speeds and create a safer environment for pedestrians. Designated crossing points such as zebra crossings, pedestrian signals, and raised medians provide pedestrians with safe and convenient opportunities to cross busy streets,

reducing the risk of accidents and improving overall pedestrian safety [24].

Moreover, integrating green spaces and trees into urban streetscapes can enhance the pedestrian experience and improve urban microclimates. Trees provide shade, mitigate urban heat island effects, and improve air quality, creating a more pleasant and comfortable walking environment. Green spaces such as pocket parks, plazas, and community gardens serve as destinations for pedestrians, encouraging walking and social interaction while also providing ecological benefits such as habitat for wildlife and storm water management. In addition to physical infrastructure improvements, promoting pedestrian culture and awareness is essential for fostering a pedestrian-friendly urban environment. Public education campaigns, community events, and pedestrian-oriented initiatives can raise awareness about the benefits of walking and encourage people to embrace walking as a viable mode of transport. Moreover, involving local communities in the planning and design process ensures that pedestrian infrastructure reflects the needs and preferences of the people who use it, leading to more inclusive and equitable outcomes [25, 26].

In conclusion, prioritizing pedestrians through urban design and infrastructure enhancement is essential for creating safer, more accessible, and livable urban environments in congested cities. By investing in wider sidewalks, pedestrian-only zones, and high-quality pedestrian infrastructure, cities can improve walkability and encourage more people to choose walking as a sustainable mode of transport. Moreover, integrating green spaces, promoting pedestrian safety, and fostering a pedestrian-friendly culture are critical components of creating vibrant and sustainable urban spaces that prioritize the needs of pedestrians.

## **2.3. Promoting Sustainable Modes of Transport and Modal Shift**

In the context of congested old Indian cities, promoting sustainable modes of transport and encouraging modal shift are essential for reducing reliance on private vehicles, alleviating congestion, and mitigating the environmental impacts of transportation. This strategy involves a multi-pronged approach that includes investing in public transit infrastructure, expanding cycling networks, promoting walking, and implementing policies and incentives to incentivize modal shift.

One key component of promoting sustainable modes of transport is investing in high-quality public

transit infrastructure. Public transit systems such as buses, metro, and suburban rail play a crucial role in providing affordable, efficient, and accessible transportation options for residents of congested urban areas. By investing in the expansion and improvement of public transit networks, cities can encourage more people to choose public transit for their daily commute, reducing congestion on roads and lowering carbon emissions associated with private vehicles. Furthermore, improving the quality and reliability of public transit services is essential for attracting the ridership and promoting modal shift. This includes measures such as increasing frequency and coverage, enhancing accessibility for people with disabilities, and implementing real-time passenger information systems. By making public transit more convenient, comfortable, and user-friendly, cities can encourage more people to leave their cars at home and opt for public transit instead [27, 28].

In addition to public transit, promoting cycling as a sustainable mode of transport can gain traction in congested old Indian cities. Cycling offers numerous benefits, including reduced congestion, improved air quality, and better public health outcomes. To promote cycling, cities can invest in dedicated cycling infrastructure such as bike lanes, bike-sharing systems, and secure bike parking facilities. Moreover, implementing traffic calming measures and reducing speed limits in urban areas can create safer conditions for cyclists and encourage more people to take up cycling for short trips.

Moreover, promoting walking as a sustainable mode of transport is essential for creating pedestrian-friendly urban environments and reducing reliance on motorized transport. Walking is not only environmentally friendly but also promotes public health and social interaction. To encourage walking, cities can invest in pedestrian infrastructure improvements such as wider sidewalks, pedestrian-only zones, and safe crossing points. Moreover, implementing policies such as pedestrian-first street design and car-free days can create a culture that prioritizes walking as a viable mode of transport. Furthermore, implementing policies and incentives to incentivize modal shift is essential for promoting sustainable modes of transport in congested cities. This includes measures such as congestion pricing, parking restrictions, and alternate day driving model, which make driving less attractive and encourage people to consider other modes of transport. Moreover, providing financial incentives such as subsidies for public transit, cycling infrastructure, and electric vehicles can further encourage modal shift and promote sustainable urban mobility [29, 30].

In conclusion, promoting sustainable modes of transport and encouraging modal shift is essential for reducing congestion, improving air quality, and creating more livable and sustainable urban environments in congested old Indian cities. By investing in public transit infrastructure, expanding cycling networks, promoting walking, and implementing policies and incentives to incentivize modal shift, cities can reduce reliance on private vehicles and create a more balanced and equitable transportation system for all residents.

#### **2.4. Integration of Land Use and Transportation Planning**

In congested old Indian cities, the integration of land use and transportation planning are crucial for creating more sustainable, efficient, and livable urban environments. This strategy involves coordinating the development of land use patterns with transportation infrastructure to minimize travel distances, reduce congestion, and promote more sustainable transport modes.

One key aspect of integrating land use and transportation planning is promoting mixed-use development and compact urban form. Mixed-use development combines residential, commercial, and recreational activities within close proximity, reducing the need for long-distance travel and promoting walking, cycling, and public transit use. By encouraging compact urban form and reducing urban sprawl, cities can create more vibrant, accessible, and sustainable urban environments. Furthermore, integrating land use and transportation planning involves prioritizing transit-oriented development (TOD) around public transit nodes such as metro stations, bus stops, and railway stations. TOD focuses development density and land uses around transit hubs, creating vibrant, walkable neighborhoods where residents can easily access public transit, shops, and amenities without relying on private vehicles. By promoting TOD, cities can maximize the efficiency of public transit investments, reduce car dependence, and create more sustainable urban communities [31].

Moreover, integrating land use and transportation planning requires designing streets and neighborhoods to prioritize pedestrians, cyclists, and public transit users over private vehicles. This includes measures such as narrowing streets, reducing parking requirements, and creating pedestrian-friendly streetscapes with wide sidewalks, tree-lined boulevards, and pedestrian plazas. By designing streets for people rather than cars, cities can create more safer, vibrant, and sustainable urban environments that prioritize human-scale mobility. In

addition, integrating land use and transportation planning involves promoting transit-oriented design (TOD) principles in urban development projects. TOD principles emphasize compact, mixed-use development, pedestrian-friendly streets, and high-quality public spaces that promote walking, cycling, and public transit use. By incorporating TOD principles into urban design guidelines and zoning regulations, cities can create more sustainable and livable urban environments that prioritize transit, pedestrians, and cyclists over private vehicles [32-35].

Furthermore, integrating land use and transportation planning requires coordinating transportation investments with land use policies to ensure that new development is served by high-quality public transit and active transportation infrastructure. This includes aligning transit expansion plans with future growth areas, investing in cycling and pedestrian infrastructure in dense urban neighborhoods, and implementing policies to reduce car dependence such as parking maximums and transportation demand management measures. By coordinating transportation investments with land use policies, cities can create more sustainable, efficient, and equitable transportation systems that support vibrant urban communities.

In conclusion, the integration of land use and transportation planning is essential for creating more sustainable, efficient, and livable urban environment in congested old Indian cities. By promoting mixed-use development, prioritizing transit-oriented development, designing streets for people, and coordinating transportation investments with land use policies, cities can create more vibrant, accessible, and sustainable urban communities that prioritize human-scale mobility and reduce reliance on private vehicles.

## **2.5. Community Engagement and Participation in Urban Planning**

In the cities, community engagement and participation in urban planning are essential for creating more inclusive, responsive, and sustainable urban environments. This strategy can be implemented involving residents, local communities, and stakeholders in the decision-making process, empowering them to contribute their knowledge, experiences, and aspirations to the planning and design of their neighborhoods.

One key aspect of community engagement is promoting participatory urban planning processes that prioritize collaboration, dialogue, and consensus-building among stakeholders. This includes organizing community meetings, workshops, and

charrettes where residents can share their ideas, concerns, and visions for the future of their neighborhoods. By involving residents in the planning process from the outset, cities can ensure that urban development projects reflect the needs, preferences, and aspirations of the people who will be affected by them. Furthermore, community engagement involves fostering partnerships and collaboration between local government agencies, community organizations, and other stakeholders to address common challenges and achieve shared goals. This includes forming community advisory boards, neighborhood associations, and public-private partnerships to facilitate ongoing dialogue and cooperation between different actors. By fostering partnerships and collaboration, cities can leverage the collective wisdom, resources, and expertise of diverse stakeholders to develop more effective and sustainable urban solutions [35-37]. Moreover, community engagement requires providing residents with access to information, resources, and opportunities to participate in the urban planning process. This includes creating user-friendly platforms for sharing information about planning projects, soliciting feedback from residents, and providing opportunities for meaningful participation. By promoting transparency, accessibility, and inclusivity in the planning process, cities can ensure that all residents have a voice in shaping the future of their communities.

In addition, community engagement involves building capacity and empowering residents to participate meaningfully in the urban planning process. This includes providing training, education, and technical assistance to community members to equip them with the knowledge, skills, and confidence to engage effectively in planning discussions and decision-making processes. By building capacity and empowering residents, cities can create more resilient, self-reliant, and empowered communities that are better equipped to advocate for their interests and aspirations. Furthermore, community engagement requires recognizing and valuing the diverse perspectives, knowledge, and experiences of different communities and social groups. This includes ensuring that planning processes are inclusive and equitable, taking into account the needs and priorities of marginalized and vulnerable populations. By actively seeking out and incorporating diverse voices and perspectives in the planning process, cities can create more inclusive, responsive, and socially just urban environments that serve the needs of all residents [38, 39].

In conclusion, community engagement and participation are essential for creating more inclusive,

responsive, and sustainable urban environments in congested old Indian cities. By involving residents, local communities, and stakeholders in the planning and design of their neighborhoods, cities can ensure that urban development projects reflect the needs, preferences, and aspirations of the people who will be affected by them. Moreover, by fostering partnerships, building capacity, and valuing diversity, cities can create more resilient, empowered, and socially just communities that are better equipped to address the challenges of urbanization and create a better future for all residents.

## **2.6. Implementing Flexible Transportation Policies and Regulatory Frameworks**

In congested old Indian cities, implementing flexible transportation policies and regulatory frameworks is crucial for adapting to changing mobility trends, addressing emerging challenges, and promoting more sustainable and efficient transportation systems. This strategy involves adopting a proactive approach to policymaking and regulation that prioritizes innovation, flexibility, and responsiveness to evolving urban mobility needs. One key aspect of implementing flexible transportation policies is adopting a multi-modal approach that recognizes the diversity of transportation options available to residents and visitors. This includes investing in a range of transportation modes such as public transit, cycling, walking, ride-sharing, and micro-mobility options like e-scooters and bike-sharing. By promoting a diverse mix of transportation options, cities can provide residents with more choice and flexibility in how they travel, reducing reliance on private vehicles and alleviating congestion on roads [40, 41].

Furthermore, implementing flexible transportation policies involves embracing emerging technologies and innovative mobility solutions to improve the efficiency and sustainability of urban transportation systems. This includes integrating digital technologies such as mobile apps, GPS tracking, and data analytics to optimize transportation services, enhance user experience, and promote more seamless and efficient mobility. By harnessing the power of technology, cities can unlock new opportunities for innovation and creativity in urban transportation, leading to more responsive and user-centric mobility solutions. Moreover, implementing flexible transportation policies requires adopting a dynamic regulatory framework that can adapt to changing mobility trends and technological advancements. This includes reviewing and updating existing regulations and standards to accommodate new transportation modes and services, such as ride-sharing, e-scooters, and autonomous vehicles. By creating a regulatory environment that fosters

innovation and experimentation while also ensuring safety, accessibility, and equity, cities can promote the development of more sustainable and inclusive transportation systems [42, 43].

In addition, implementing flexible transportation policies involves adopting a data-driven approach to decision-making and performance monitoring. This includes collecting and analyzing data on transportation patterns, travel behavior, and user preferences to inform policymaking, improve service delivery, and optimize resource allocation. By leveraging data and analytics, cities can gain valuable insights into transportation trends and challenges, identify opportunities for improvement, and measure the impact of policy interventions on mobility outcomes. Furthermore, implementing flexible transportation policies requires fostering collaboration and partnership between government agencies, private sector stakeholders, and civil society organizations. This includes establishing forums for dialogue and cooperation, sharing best practices and lessons learned, and leveraging the collective expertise and resources of diverse stakeholders to address common challenges and achieve shared goals [44]. By fostering collaboration and partnership, cities can create a more inclusive and participatory decision-making process that reflects the interests and priorities of all stakeholders involved in urban transportation.

In conclusion, implementing flexible transportation policies and regulatory frameworks is essential for promoting more sustainable, efficient, and inclusive transportation systems in congested old Indian cities. By adopting a multi-modal approach, embracing emerging technologies, and fostering collaboration and partnership, cities can create more responsive and user-centric transportation systems that meet the diverse needs and preferences of residents and visitors. Moreover, by adopting a data-driven approach and embracing innovation, cities can unlock new opportunities for improvement and innovation in urban mobility, leading to a more sustainable and resilient urban future.

## **2.7. Incorporating Climate Resilience and Environmental Sustainability in Transportation Planning**

In congested old Indian cities, incorporating climate resilience and environmental sustainability in transportation planning is critical for mitigating the impacts of climate change, reducing greenhouse gas emissions, and promoting more sustainable and resilient transportation systems. This strategy involves adopting a holistic approach to transportation planning that considers the environmental, social, and economic

implications of transportation decisions and prioritizes actions to reduce carbon emissions, improve air quality, and enhance resilience to climate-related hazards. One key aspect of incorporating climate resilience and environmental sustainability in transportation planning is promoting low-carbon and renewable energy sources for transportation. This includes investing in electric vehicles (EVs), hybrid vehicles, and other alternative fuel vehicles (AFVs) that produce fewer emissions than traditional gasoline and diesel vehicles [45]. By transitioning to cleaner and more sustainable modes of transport, cities can reduce their carbon footprint and improve air quality, leading to healthier and more livable urban environments. Furthermore, incorporating climate resilience and environmental sustainability in transportation planning involves promoting active transportation modes such as walking and cycling, which have minimal environmental impact and provides numerous health and social benefits. This includes investing in cycling infrastructure such as bike lanes, bike-sharing systems, and secure bike parking facilities to encourage more people to cycle for short trips and reduce their reliance on motorized transport. By promoting active transportation, cities can reduce congestion, improve public health, and enhance the overall quality of life for residents [46].

Moreover, incorporating climate resilience and environmental sustainability in transportation planning requires integrating climate change considerations into infrastructure planning and design. This includes assessing the vulnerability of transportation infrastructure to climate-related hazards such as flooding, extreme heat, and sea-level rise, and implementing measures to enhance resilience and adaptability. By designing transportation infrastructure to withstand climate-related risks and uncertainties, cities can reduce the potential for disruption and damage and ensure the continued functionality and reliability of transportation systems in the face of a changing climate. In addition, incorporating climate resilience and environmental sustainability in transportation planning involves promoting land use policies and urban design strategies that reduce the need for long-distance travel and promote more compact, mixed-use development patterns. This includes promoting transit-oriented development (TOD) around public transit nodes, supporting mixed-use development that reduces travel distances, and creating walkable, bikeable neighborhoods with access to shops, services, and amenities. By promoting more sustainable land use patterns, cities can reduce greenhouse gas emissions, alleviate congestion, and enhance the resilience of urban transportation systems to climate change impacts [47, 48].

Furthermore, incorporating climate resilience and environmental sustainability in transportation planning requires fostering public awareness and engagement around climate change and sustainable transportation issues. This includes educating residents about the environmental impacts of transportation choices, promoting behavior change through campaigns and initiatives, and encouraging participation in sustainable transportation options such as carpooling, public transit, and cycling. By raising awareness and empowering residents to take action, cities can build a culture of sustainability and resilience that supports the transition to more sustainable and resilient transportation systems.

In conclusion, incorporating climate resilience and environmental sustainability in transportation planning is essential for promoting more sustainable, efficient, and resilient transportation systems in congested old Indian cities. By promoting low-carbon and renewable energy sources, investing in active transportation infrastructure, integrating climate change considerations into infrastructure planning and design, promoting sustainable land use policies, and fostering public awareness and engagement, cities can reduce their carbon footprint, improve air quality, and enhance the resilience of urban transportation systems to climate change impacts. Moreover, by taking proactive action to address climate change and promote sustainability, cities can create more healthier, livable, and resilient urban environments for current and future generations.

## **2.8. Intelligent Geotechnical Monitoring in Urban Infrastructure**

In old Indian city cores, where underground space is scarce and heritage structures coexist with new infrastructure, foundation performance plays a critical role in ensuring long-term stability. Intelligent geotechnical monitoring offers a way to continuously assess subsurface conditions beneath parking decks, basements, and pedestrian tunnels. This approach employs embedded sensors such as strain gauges, piezometers, inclinometers, and distributed fiber-optic sensors to record stress, deformation, and pore-water pressure in real time. This integration of advanced monitoring technologies can significantly enhance the understanding of foundation behavior and improve decision-making for maintenance and safety in heritage-rich urban environments [49].

By integrating these data streams with smart urban mobility platforms, engineers can detect settlement trends or early signs of ground movement that may endanger pedestrian pathways or parking structures.

Artificial intelligence algorithms can analyze these continuous datasets to identify anomalous behavior, correlate it with traffic-induced vibrations or rainfall events, and predict future instability.

Cities such as Delhi and Kolkata, with ongoing underground metro and parking developments, already use such monitoring to assess differential settlement during construction. Extending this approach to surface-level pedestrian networks and multi-tier parking systems can prevent failures, reduce maintenance costs, and extend the operational life of urban infrastructure. This proactive strategy not only enhances safety but also promotes sustainable urban development by minimizing disruptions and preserving the integrity of heritage structures.

### **2.9. Soil-Structure Interaction in Pedestrian and Parking Systems**

Sustainable infrastructure design requires understanding how structures interact with the supporting soil under repeated dynamic loading from vehicles and pedestrians. In congested Indian cities, subsoils often comprise variable fills, reclaimed materials, and heterogeneous historical layers, resulting in uneven settlement or lateral deformation that can compromise structural integrity. Therefore, assessing the influence of these soil conditions is critical for ensuring the resilience of urban infrastructure [50].

Modeling soil-structure interaction (SSI) using numerical tools such as PLAXIS 2D/3D, FLAC3D, or OpenGeoSys allows engineers to simulate how underground parking basements, retaining walls, or pedestrian underpasses respond to transient loads and moisture fluctuations. Coupled hydro-mechanical analysis can also predict deformation due to fluctuating groundwater levels or monsoon infiltration and assess the long-term stability of structures in varying soil conditions. Understanding these interactions is essential for developing resilient urban infrastructure that can withstand environmental challenges. The integration of advanced modeling techniques is vital for optimizing the design and performance of urban infrastructure, particularly in regions with complex soil profiles [51, 52].

Integrating SSI results into sustainable mobility planning ensures that proposed infrastructure solutions—such as smart parking systems or elevated pedestrian corridors—are geotechnically compatible with site conditions. This combined perspective of geotechnical stability and urban usability defines the next generation of resilient city design.

### **2.10. AI-Based Geotechnical Assessment for Urban Redevelopment**

Artificial intelligence (AI) and machine learning (ML) have emerged as transformative tools in geotechnical engineering, capable of processing heterogeneous datasets from in-situ sensors, satellite imagery, and borehole records. In the context of congested old Indian cities, AI-driven geotechnical assessment can support predictive modeling of subsurface behavior beneath parking and pedestrian infrastructure [53, 54].

Supervised learning models can estimate settlement, bearing capacity, or groundwater response based on limited geotechnical investigation data. Neural network-based digital twins can simulate dynamic ground conditions in response to traffic loading or climate-induced moisture variations. When integrated with urban mobility datasets, these models allow engineers to evaluate how ground deformation might influence pedestrian flow, pavement performance, or parking structure stability [55, 56].

In practical terms, the AI workflow may begin with automated data ingestion from geotechnical investigations, monitoring instruments, and urban mobility platforms into a unified database. Feature engineering can then be used to derive composite indicators, such as traffic-induced stress indices or moisture deficit factors, which improve model interpretability for practicing engineers. Model outputs can be mapped spatially in the form of “risk heatmaps” overlaid on city base plans, allowing planners to identify sensitive corridors where additional loading from parking decks or pedestrian structures should be carefully controlled. Over time, continuous learning algorithms can update model parameters as new monitoring data become available, reducing epistemic uncertainties associated with old, poorly documented ground conditions. Scenario-based simulations can further be used to test “what-if” questions, such as the effect of concentrating parking demand on one block versus another before committing to costly construction. In this way, AI does not replace conventional geotechnical analysis, but acts as an intelligent decision-support layer that helps prioritize investigations, optimize monitoring layouts, and align geotechnical risk management with broader sustainable mobility goals.

Such AI-assisted assessments not only improve reliability and safety but also enable adaptive management of infrastructure in dense, evolving cityscapes. The convergence of data science and geotechnical insight marks a shift toward intelligent, proactive urban redevelopment strategies.

### 3. CHALLENGES

Implementing sustainable solutions for parking and pedestrian management in congested old Indian cities comes with its own set of challenges. These strategies not only hold promise for addressing urban congestion and promoting more sustainable urban mobility but also face several hurdles that need to be overcome for successful implementation.

One significant challenge is the lack of adequate funding and resources for infrastructure development and maintenance. Many old Indian cities grapple with limited financial resources and competing priorities, making it difficult to invest in the necessary infrastructure improvements for parking and pedestrian management. Additionally, the high land cost in urban areas poses a barrier in creating new parking facilities and pedestrian infrastructure, further exacerbating the challenge of inadequate funding. To overcome this challenge, cities must explore innovative financing mechanisms such as public-private partnerships, value capture mechanisms, and dedicated funding streams for sustainable transportation projects [57, 58]. Another challenge is the complex regulatory environment and bureaucratic hurdles that can slow down the implementation of sustainable transportation solutions. In many cases, outdated regulations and cumbersome approval processes hinder the adoption of new technologies and innovative approaches to parking and pedestrian management. Additionally, overlapping jurisdictions and fragmented governance structures can lead to coordination challenges between different government agencies and stakeholders involved in urban planning and transportation. To address this challenge, cities must streamline regulatory processes, harmonize standards and guidelines, and foster collaboration and coordination among relevant stakeholders [59, 60].

Moreover, cultural and behavioral barriers present challenges in promoting sustainable modes of transport such as walking, cycling, and public transit. In many Indian cities, there is a strong cultural preference for private vehicle ownership, fueled by perceptions of status, convenience, and safety. Additionally, concerns about personal security, comfort, and reliability often deter people from using public transit or active modes of transport. Changing entrenched behaviors and attitudes towards transportation requires targeted education and outreach campaigns, as well as investments in infrastructure and amenities that make walking, cycling, and public transit more attractive and accessible options for residents. Infrastructure constraints pose another significant challenge to implementing sustainable transportation solutions in

congested old Indian cities [61]. Many older cities have narrow streets, limited right-of-way, and densely built environments that make it difficult to retrofit existing infrastructure or create new facilities for parking and pedestrian management. Additionally, the rapid pace of urbanization and informal development in these cities have led to encroachments on sidewalks, streets, and public spaces, further complicating efforts to improve pedestrian infrastructure and create dedicated parking facilities. To overcome this challenge, cities must adopt a flexible and context-sensitive approach to infrastructure planning and design, leveraging innovative solutions such as modular and adaptable infrastructure elements, shared space concepts, and tactical urbanism interventions [62].

Furthermore, political will and leadership are critical for driving forward sustainable transportation initiatives in congested old Indian cities. However, political dynamics, vested interests, and short-term electoral cycles can sometimes impede progress on sustainable transportation goals. Additionally, conflicting priorities and competing agendas among different levels of government and political parties can lead to policy inertia and delays in decision-making. To overcome this challenge, cities must build consensus among key stakeholders, engage political leaders and decision-makers, and demonstrate the social, economic, and environmental benefits of sustainable transportation initiatives [63].

In geotechnical context, old Indian city cores are typically underlain by highly heterogeneous soils, often comprising uncontrolled fills, relic foundations, buried utilities, and locally variable alluvium that complicate reliable characterization. Historical absence of systematic ground improvement or compaction means that many near-surface strata exhibit low stiffness and high compressibility, increasing the risk of long-term settlement under new parking and pedestrian infrastructure. High groundwater tables, leaking water and sewer lines, and inadequate drainage frequently lead to subgrade soils softening and effective stress reduction, especially during monsoon periods. Proximity of closely spaced, lightly founded masonry buildings limits allowable ground movements and imposes stringent deformation criteria on any excavation or foundation works. The presence of old trees, basements, and undocumented service corridors introduce anisotropy and local discontinuities that are difficult to capture in conventional site investigations. Together, these factors make geotechnical design in old Indian city soils strongly uncertainty-driven, requiring conservative soil-structure interaction assumptions and a greater reliance on staged construction, monitoring, and adaptive design.

In congested heritage cores, foundation design is constrained by the narrow plots, irregular building lines, and immediate proximity of age-sensitive masonry structures that can tolerate only very small differential settlements. Deep foundations or basement excavations for parking structures must be configured to minimize lateral soil movements and vibration, while also respecting strict clearance requirements from existing footings, underground utilities, and heritage facades. Temporary excavation support systems are difficult to install and sequence in such constricted spaces, and construction logistics limit the access, restrict working hours, and safety requirements for pedestrians and traffic often govern the feasible design more than pure bearing capacity or stability considerations. High groundwater levels and weak, heterogeneous fills further complicate dewatering and retaining-wall behaviour, increasing the importance of staged excavation, real-time monitoring, and contingency measures to avoid damage to adjacent heritage assets.

In conclusion, while implementing sustainable solutions for parking and pedestrian management in congested old Indian cities presents several challenges, overcoming these hurdles is essential for creating more livable, resilient, and sustainable urban environments. By addressing funding constraints, streamlining regulatory processes, addressing cultural and behavioral barriers, overcoming infrastructure constraints, and fostering political will and leadership, cities can unlock the full potential of sustainable transportation solutions and pave the way for a more sustainable urban future.

#### **4. RISK AND FAILURE MODES IN GEOTECHNICAL-URBAN ENVIRONMENTS NEAR HERITAGE STRUCTURES**

Risk assessment in geotechnical-urban environments must account for the tight coupling between subsurface behaviour, built heritage, and dynamic mobility loads in congested city cores. In old Indian cities, potential failure modes include excessive total and differential settlements of pavements and parking slabs, tilting or cracking of adjacent masonry facades, leakage and uplift in underground parking basements, and localized bearing failures beneath overloaded street edges or informal parking strips. These mechanisms are often exacerbated by high groundwater levels, ageing utilities, and episodic load amplification during peak traffic or festival periods, which can drive soil-structure interaction beyond the assumptions of conventional design. From a risk perspective, even small deformations that would be tolerable in greenfield settings can be critical when they threaten heritage structures, narrow rights-of-way, or heavily used pedestrian corridors [64].

A structured risk assessment framework therefore needs to combine geotechnical hazard characterization (e.g., compressible layers, low shear strength zones, tunnelling influence zones) with exposure indicators such as building vulnerability, pedestrian density, and criticality of transport links. Probabilistic or semi-quantitative approaches, including risk matrices and vulnerability scoring, can be used to rank street segments and blocks where new parking or pedestrian infrastructure is proposed. Within the intelligent geotechnical framework, monitoring data from inclinometers, settlement markers, and structural sensors provide early warning when measured trends deviate from predicted performance envelopes, signalling an increased likelihood of failure modes such as wall rotation, slab settlement, or joint opening in pavements. AI-enabled models can further refine risk estimates by correlating time-series measurements with traffic patterns and rainfall, thereby identifying combinations of loading and environmental conditions that precede distress [65, 66].

In practical terms, risk assessment outcomes should inform decisions on allowable load increments from multi-level parking, selection of foundation systems, and the extent of ground improvement or underpinning required near heritage assets. High-risk corridors may warrant stricter deformation criteria, more conservative serviceability limits, and denser monitoring layouts, while lower-risk areas can adopt more flexible design and operational strategies. By explicitly linking potential failure modes to both geotechnical and urban consequences, the proposed framework encourages proactive mitigation such as drainage upgrades, phased excavation, or traffic management rather than reactive repairs after damage has occurred.

#### **5. PRACTICAL GUIDELINES AND RECOMMENDATIONS FOR INTEGRATING GEOTECHNICAL INTELLIGENCE IN URBAN DEVELOPMENT**

Practical integration of geotechnical intelligence into urban development in old Indian city cores begins with treating subsurface information as a primary planning layer, not a late-stage design input. Master plans and mobility schemes for parking and pedestrian infrastructure should be underpinned by city-scale geotechnical zoning maps that combine borehole data, historical construction records, and known problem areas such as collapsible fills or high groundwater pockets. For high-risk corridors and heritage precincts, authorities should mandate a minimum level of site investigation and baseline monitoring (e.g., settlement markers, groundwater observation wells) before approving deep excavations or multi-level parking

structures. Intelligent monitoring systems using inclinometers, strain gauges, fiber-optic sensors, or pavement performance metrics should be embedded into new geotechnical works from the outset, with clearly defined trigger levels and response actions for contractors and municipal engineers [67, 68].

To make such systems actionable, data from geotechnical instruments must be integrated with traffic, parking occupancy, and pedestrian flow datasets on a common platform, enabling joint interpretation by geotechnical, structural, and transport planners. Simple risk-informed decision rules can then be adopted, such as tightening deformation limits and increasing monitoring density in zones where vulnerable masonry buildings coincide with high pedestrian volumes or critical access routes. Where legacy infrastructure and undocumented ground conditions dominate, guidelines should emphasize incremental, observational approaches, with staged excavation, real-time back-analysis, and the flexibility to adjust support systems as measurements deviate from predictions. AI-based tools, once calibrated with local data, can support authorities by prioritizing blocks for detailed investigation, suggesting optimal sensor layouts, and flagging emerging anomalies in settlement or wall movement trends before visible damage occurs [69].

From a governance perspective, municipalities should develop standard protocols for storing and sharing geotechnical and monitoring data, so that each new project incrementally enriches the urban "subsurface knowledge base" instead of starting from scratch. Professional guidelines can also encourage early multi-disciplinary reviews where geotechnical specialists are involved in framing mobility projects, not only in checking foundation designs. Finally, demonstration projects such as a pilot intelligent parking, pedestrian facility in a heritage core can help translate abstract recommendations into replicable practice and build institutional confidence in geotechnical intelligence as a routine component of sustainable urban redevelopment.

## CONCLUSIONS

Creating sustainable parking and pedestrian systems in Indian cities requires moving beyond surface-level planning to include the often-overlooked geotechnical foundations that sustain urban life. Integrating intelligent geotechnical monitoring, soil-structure interaction modeling, and AI-driven assessment can revolutionize conventional urban mobility systems, making them more smarter, safer, and adaptable. This integrated framework links sustainable transport planning with real-time subsurface intelligence, ensuring that urban

infrastructure remains stable under heavy loads, fluctuating groundwater levels, and changing environmental conditions.

By merging sustainability principles with data analytics and geotechnical science, cities can adopt a development model that is both human-centered and geotechnically sound. Intelligent monitoring tools and predictive analytics enable proactive maintenance, reducing risks of settlement, deformation, or failure beneath parking facilities and pedestrian corridors. This approach enhances infrastructure resilience while minimizing resource consumption and maintenance costs.

Ultimately, embedding geotechnical intelligence within sustainable mobility planning fulfills the broader objectives of intelligent geotechnical engineering, creating urban systems that are efficient on the surface and secure beneath it. The framework provides a scalable pathway for India's heritage-rich, high-density cities to achieve long-term structural safety, mobility efficiency, and environmental resilience in the face of accelerating urbanization and climate variability.

## CONFLICTS OF INTEREST

Author declares that there is no conflict of interests concerning the publication of this manuscript.

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