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Integrative Analysis of Impacts of Environmental Pollutants and Sociocultural Effects in Urban Highway Construction

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ABSTRACT

This study explores the multifaceted impacts of environmental pollution from highway construction projects in urban settings, focusing on Tehran City as a case study. Urban highway construction projects, critical for enhancing infrastructure and connectivity, inevitably bring about significant environmental and social changes. This research employs a Causal Loop Diagram (CLD) methodology to dissect the direct and indirect consequences of these projects on the urban environment and its residents. The findings reveal that construction activities substantially contribute to air and noise pollution, which adversely affect the quality of life and health of urban populations. Disturbances such as dust, emissions, and constant noise not only deteriorate air quality but also lead to a series of socio-economic issues including decreased property values and increased health-related expenditures. Additionally, the disruption of local ecosystems and water bodies exacerbates the environmental footprint, leading to a decline in biodiversity and the degradation of natural habitats. Social impacts are equally significant, with communities experiencing increased stress and disruption, which often manifest as public dissent towards development projects. This study highlights the critical need for integrating environmental management and social engagement strategies in the planning and execution phases of urban highway projects. By doing so, it is possible to mitigate negative impacts and enhance the overall sustainability of urban development projects, ensuring that the infrastructure improvements are balanced with environmental conservation and social well-being.

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INTRODUCTION

Environmental contamination at construction sites is a widely recognized issue that adversely affects the three pillars of sustainability—economic, environmental, and social—of the impacted community and its surrounding ecosystems. The development of highways in densely populated urban zones, alongside the provision of various opportunities for the residents therein, is invariably perceived as a significant challenge (Lima et al., 2021). The critical role of highways lies in their expansive coverage and contribution to enhancing regional infrastructure. Urban planners are consistently confronted with the need to address the uneven and expansive growth in cities. Therefore, the construction of highways to improve urban inhabitants' access to a diverse array of facilities and services becomes essential. However, the

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paramount concern in this domain is to diminish the environmental and societal repercussions of highway construction. This objective is attainable through a thorough evaluation of the social and environmental impacts associated with such projects.

Pollution related to environmental aspects, primarily manifesting throughout construction phases, often positions the construction entity at the forefront of accountability (Cheriyan & Choi, 2020; Houser & Pruess, 2009). However, the role of additional contributory factors like modifications in orders, discrepancies in design, and alterations in project timelines, which engage stakeholders beyond the construction site, including designers and clients, has not been sufficiently considered (Shrestha et al., 2014).

Miao et al. (2015) posited that while enterprises engaging in construction activities are immediate sources of environmental degradation, attributing sole responsibility to them is overly simplistic (Miao et al., 2015). Their actions, potentially stemming from inadequate oversight by local governing bodies, are part of a broader context. Environmental incidents may also emerge from external determinants, for instance, the cost-cutting tendencies of clients, in addition to the initiating factors from the construction firms themselves. Typically, these external determinants also termed latent factors, are overlooked, failing to acknowledge their pivotal role where interventions by upstream entities set the stage for the emergence of initiating factors (Goncalves Filho et al., 2021). Hence, it is imperative to acknowledge both the direct and latent contributors in the analysis of any environmental event.

Identification of underlying factors in the construction sector, particularly in highway project initiatives, can be gleaned through the development of causal theories within domains such as safety, productivity, and sustainability (Liu et al., 2020; Onat et al., 2014). However, a Scopus inquiry with the phrase 'causal theory in construction' predominantly reveals its application within the spheres of environmental pollution and societal repercussions in construction. There is scant research focused on environmental aspects, especially the implications of pollution in highway construction undertakings. This observation is corroborated by Fuertes et al. (2013), who asserted the scarcity of environmental research illustrating causal frameworks, is possibly attributed to the challenges in discerning the connections between causative elements and environmental outcomes (Fuertes et al., 2013).

Yuan et al. (2014) delved into the interplay among three performance metrics (economic, environmental, and social) that form the foundational variables of construction waste management practices via causal loop diagrams (Yuan et al., 2014). The causal framework, embodied by these diagrams, furnishes a framework upon which a quantitative model to evaluate the impacts of management strategies on efficacious construction waste management can be crafted.

Belayutham et al. (2016) employed an accident causation framework to delineate the distal and proximal determinants of site water pollution, which are depicted through the Causal Loop Diagram (Belayutham et al., 2016). Their findings indicate that distal factors precipitate a cascading influence on proximal factors, where the intricate interplay between the two may significantly heighten the likelihood of site water contamination.

A comparative study of environmental policies related to ECPs (EREPs) in China and the United States examined historical data from 1960 to 2018 and applied text-mining analysis to data from 2009 to 2019 (Wu et al., 2022). The results highlight key differences: (1) the EREP framework includes external factors and internal EPs; (2) China's policies follow periodic, plan-oriented trends, while U.S. policies are more explanatory; (3) Chinese EPs focus on pollution control, whereas U.S. policies prioritize human health impacts; and (4) both countries place less emphasis on project-level environmental protection measures. This study offers a comparative analysis of EREPs in two major nations, emphasizing how these policies reflect broader national contexts. The findings provide a basis for further research into the evolution and innovation of environmental policies, particularly in countries facing large-scale expressway developments.

In the domain of environmental impact assessments concerning infrastructure projects, particularly highways, a multitude of scholarly articles, reports, and guidelines have been developed employing various evaluative matrices. Among these scholarly works, a number draw upon the foundational principles of the Leopold matrix, while others adopt enhanced or altered versions of this evaluative framework (Aghnoum et al., 2014; Alam et al., 2011; Anile et al., 1995; Asadollahfardi & Asadi, 2018; Canteiro et al., 2018; Darbra et al., 2005; Hafezi Moghaddas & Hajizadeh Namaghi, 2009; Ho et al., 2018; Jaskólski et al., 2018; Josimovic et al., 2014; Kaercher et al., 2013; Kist et al., 2009; Nahvi et al., 2017; Rashid et al., 2013; Sajjadi et al., 2017; Valizadeh & Hakimian, 2018)

In the realm of environmental and social impact assessments for highway projects, the National Works Agency's 2017 study stands out. This particular evaluation scrutinized the environmental repercussions associated with the Harbour View to Yallahs highway segment in Kingston and St. Thomas, utilizing a comprehensive environmental impact assessment matrix. This matrix was meticulously applied to assess impacts across various dimensions: physical, biophysical, and socio-human, throughout the construction and operational phases of the highway (NWA, 2017)

The assessment's matrix is intricate, detailing the characteristics of impacts as either beneficial or detrimental. It evaluates the severity of impacts as low, medium, or high, and categorizes their duration as either transient or enduring. Moreover, the matrix delineates the extent of impacts, whether they are local, regional, or national, and classifies the influence as either direct or indirect. Crucially, it appraises the significance of these impacts, considering a range of factors such as legal stipulations, the potential jeopardy to endangered flora and fauna, the cumulative nature of impacts, their reversibility, and the likelihood of their occurrence (Samy-Kamal et al., 2023).

This methodical approach is not unique to this instance but reflects a broader trend in the environmental assessment of highways, where similar matrices are routinely employed (Hoxha et al., 2021). However, it is worth noting that some guidelines propose a more constrained examination of impacts, focusing on fewer dimensions (TCN & PMU, 2016).

In contrast, various other environmental and social impact assessment documents have employed the impact assessment matrix solely to evaluate the nature and scale of impacts during both the construction and operational stages of different interventional initiatives (EBK, 2017, 2018; Ltd, 2016; NRA, 2008). These evaluations have taken into account various factors such as size, nature, sustainability, and reversibility, employing a qualitative approach within the framework of impact assessment matrices (Palmer, 2022).

Moreover, certain guidelines and reports on environmental and social impact assessments have delineated the vulnerability and value of regions impacted by projects. This delineation categorizes the impact into four distinct levels: negligible, low, moderate, and high, or evaluates the severity of impact across four analogous dimensions: rate, persistence, reversibility, and frequency, all within a matrix format. This method systematically categorizes the impacts on environmental and social factors during the construction and operational phases into one of four classifications: high, moderate, low, or negligible (URS & UK, 2014a, 2014b).

Conversely, in additional reports concerning environmental and social impact assessments, the matrix for assessing impacts is developed by juxtaposing the likelihood of impact occurrence with the consequences thereof. Subsequently, this stratifies the inflicted impacts on various social and environmental elements during the construction and operational stages into three distinct categories: high, medium, and low (Murtagh et al., 2020). In a related guideline, the matrix for assessing social and environmental impacts is constructed by comparing the extent of impact on beneficiaries against its significance (TAP, 2013). This approach underpins a comprehensive multi-tiered framework designed to evaluate the environmental and social interaction impacts of highway construction, advocating for the integrated execution of the ESIA process, as opposed to the isolated application of EIA and SIA.

In conclusion, this study aims to dissect the multifaceted environmental and societal challenges associated with urban highway construction. By employing a Causal Loop Diagram, this research endeavors to unravel the intricate web of direct and latent factors contributing to environmental degradation and social disruption. Through a detailed examination of the Tehran Municipality as a case study, the study aspires to offer a nuanced understanding of the consequences of highway construction, guiding policymakers and urban planners toward sustainable development practices. Ultimately, the goal is to foster a harmonious balance between urban expansion and the preservation of environmental and social integrity, ensuring that the benefits of infrastructure development are not overshadowed by its costs to society and nature.

MATERIALS & METHODS

A Causal Loop Diagram (CLD) serves as a formidable instrument for delineating the feedback architecture inherent within systems. This diagram, comprising an array of variables interconnected by arrows, delineates the causal dynamics at play between these variables. The interplay between two elements, A and B, exemplifies a causal linkage: a modification in A instigates a corresponding alteration in B, assuming the constancy of other variables. Such causal interconnections may manifest as either positive or negative: a congruent movement between cause and effect signifies a positive correlation, whereas an inverse relationship indicates a negative correlation.

Anchored in systems theory and systems thinking, a pivotal aspect here is the feedback mechanism, which serves as the circuit's completion. After this phase, the development of the state and flow diagram ensues, offering a refined visual representation of the system's dynamics.

Creating a Causal Loop Diagram (CLD) involves several key steps (Bala et al., 2017; Haraldsson et al., 2006):

1. Identify the Challenge: Define the core issue, its nature, and its impacts within the system's boundaries.
2. Frame the Inquiry: Clarify the specific question the CLD will address; use separate CLDs if multiple questions arise.
3. Prioritize Key Elements: List all relevant variables and rank them by importance, focusing on critical ones while refining as needed.
4. Develop a Preliminary CLD: Connect variables, ensuring feedback loops are logical and cohesive, adding more as the model evolves.
5. Construct Reference Behavior Patterns (RBPs): Use RBPs to highlight feedback dynamics, aligning the model's behavior with observed patterns.
6. Validate the CLD: Confirm that the initial CLD accurately represents the intended dynamics.
7. Refine Iteratively: Enhance accuracy by revisiting the CLD based on new insights from discussions.
8. Draw Conclusions: Assess whether the CLD answers the original question or requires modifications to realign with the research focus.

Vensim is an advanced software suite designed for enhancing system efficiency through dynamic modeling and simulation. It supports model creation, evaluation, and dissemination, offering tools like cause-and-effect diagrams and Causal Loop Diagrams (CLDs) to map complex interactions (Lambraki et al., 2022). In this study, Vensim was used to construct a CLD illustrating the environmental and social impacts of urban highway infrastructure, adhering to established modeling norms.

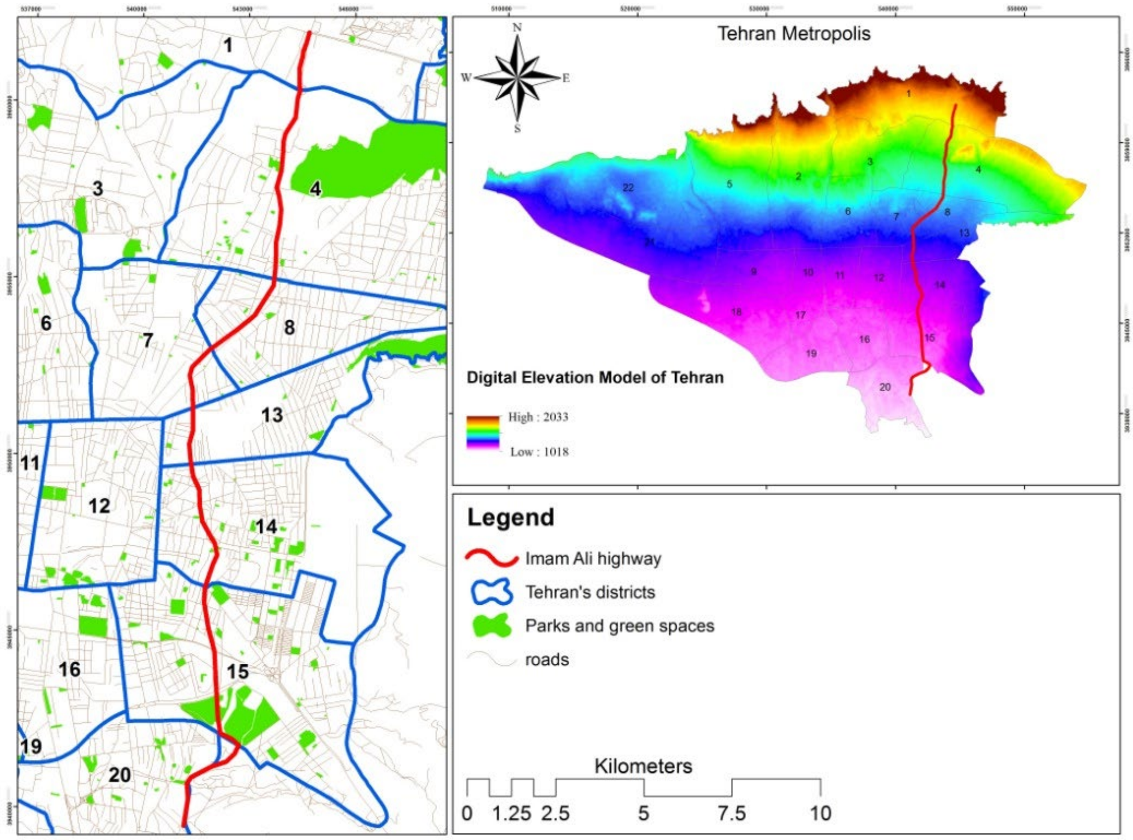

Fig. 1. Highway selected for study in Tehran

In Tehran, expanding arterial roadways has improved connectivity and aligned with strategic city objectives, exemplified by the Imam Ali Expressway (Fig. 1). This 35-kilometer project spans eight districts, revitalizing urban areas, bolstering economic activities, resolving 5,029 legal issues, and freeing over 1 million square meters of land. Despite the extensive expressway network, Tehran still faces significant traffic congestion, with this highway serving as a critical development in the eastern quadrant, intersecting multiple districts and highlighting its importance in urban planning and infrastructure.

RESULTS AND DISCUSSIONS

This section examines the environmental and social impacts of urban highway construction in Tehran, using Causal Loop Diagram (CLD) analysis to reveal complex relationships within the city's urban landscape. The CLD offers a holistic view of immediate and long-term effects, showing how factors like economic, regulatory, and social dynamics shape outcomes. This approach provides critical insights for sustainable urban planning by highlighting both environmental burdens (e.g., air and noise pollution, soil degradation, and water contamination)

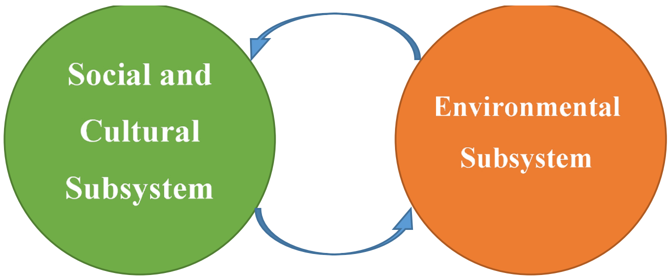

Fig. 2. Block diagram of the interconnected subsystems

and social impacts (e.g., public health, community interactions, and cultural shifts). Data were collected through field observations, municipal reports, and interviews with over 65 local residents, capturing a grassroots perspective on the project's effects. These diverse inputs enriched the CLD model, allowing us to map detailed cause-and-effect relationships and identify feedback loops. The findings emphasize the need for thoughtful interventions to mitigate negative outcomes and enhance positive impacts, ultimately guiding more resilient and community-centered urban development.

Based on the subsystems presented in Figure 2, the relationship between the environmental and social subsystems in the context of urban highway construction can be intricately connected through multiple feedback loops and direct interactions. Environmental issues, such as pollution, habitat destruction, and noise, directly affect public health, residential satisfaction, and community stability. These disruptions lead to social consequences like increased healthcare costs, decreased property values, and potential displacement. Within the environmental subsystem, diverse impacts arise, including air and noise pollution, solid waste, soil degradation, and water contamination. Key aspects like waste management, Health, Safety, and Environment (HSE) compliance, and pollution control measures determine the project's environmental footprint. These factors emphasize the need for responsible urban planning that integrates environmental conservation with project development.

Causal Loop Diagram (CLD) modeling effectively captures the interdependencies within the environmental subsystem. The CLD uses nodes to represent environmental variables and arrows to illustrate causal influences, helping predict outcomes, plan interventions, and understand unintended consequences. This dynamic tool enables stakeholders to simulate scenarios and make strategic decisions to minimize environmental impacts while pursuing construction goals.

As Shown in Fig. 3, the "Causes Tree" diagram provides a hierarchical view of the factors driving environmental degradation, categorizing primary causes (e.g., emissions, dust, runoff) and tracing their effects through secondary and tertiary causes. These pollutants exacerbate issues like respiratory and cardiovascular health problems, which contribute to social inequalities. The diagram highlights how integrated strategies, such as improved construction practices and regulatory frameworks, are essential to mitigating environmental and social impacts. By

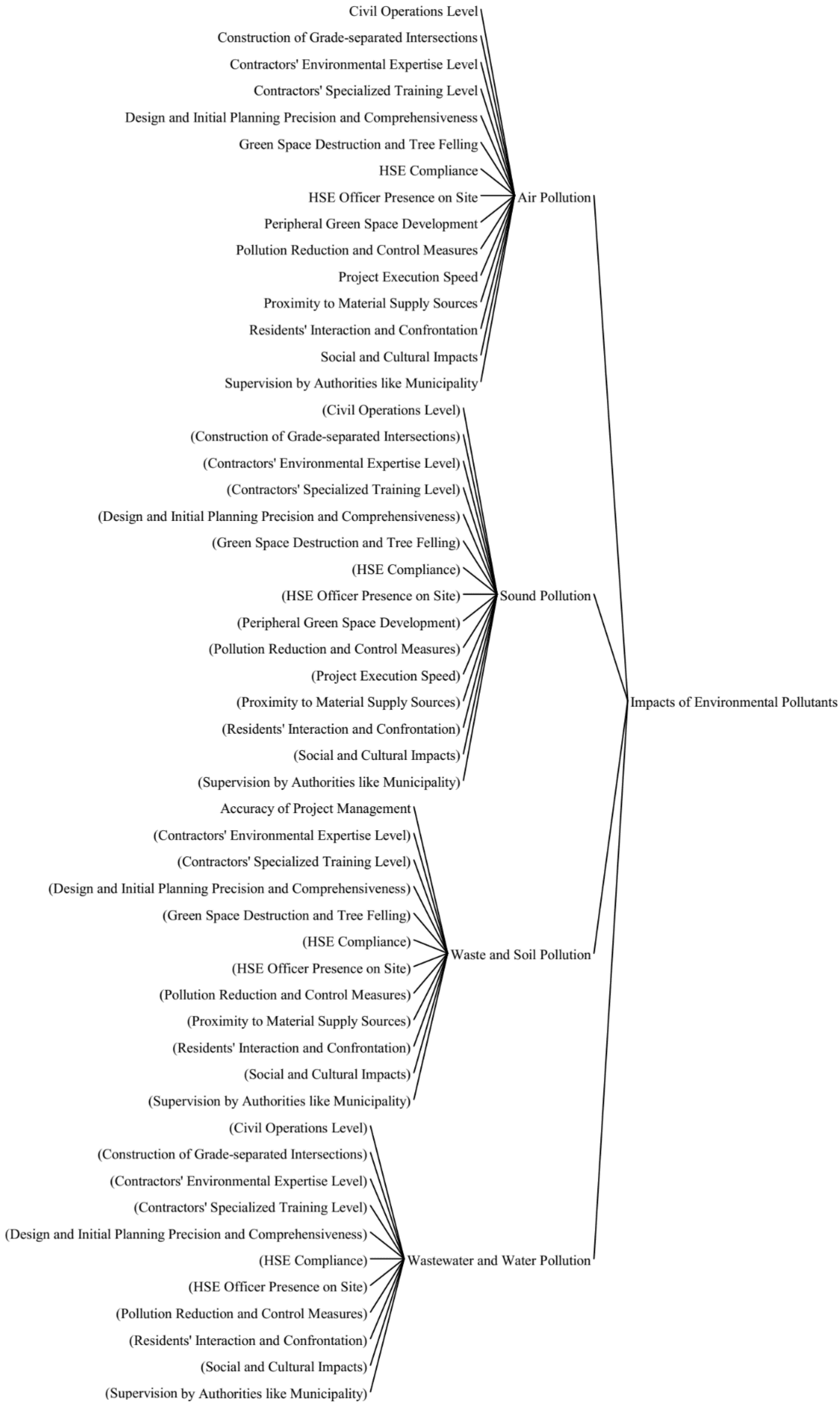

Fig. 3. Causes tree of Impacts of Environmental Pollutants

linking pollutants to broader social and ecological consequences, the "Causes Tree" emphasizes the need for comprehensive environmental management in urban infrastructure projects.

The CLD of the Environmental Subsystem, as depicted in Figure 4, offers a comprehensive overview of the multifaceted factors affecting environmental pollution, extending beyond mere pollutants. The diagram intricately illustrates how "Air Pollution" is not only intensified by "Traffic Congestion" but also by "Green Space Destruction and Tree Felling," which diminishes the natural absorption capacity of the environment. Additionally, "Soil Pollution" is often aggravated by construction-related waste and pollution, necessitating interventions such as soil stabilization and strict waste management protocols. Similarly, "Water Pollution" from construction activities is closely monitored under rigorous Health, Safety, and Environment (HSE) regulations to ensure proper waste treatment and disposal. The presence of an HSE officer on-site is pivotal, directly influencing the efficacy of pollution control measures.

The Causal Loop Diagram (CLD) in Figure 4 highlights the social and cultural impacts of urban infrastructure projects, illustrating complex causal links between construction activities and social consequences. Key factors identified include community displacement, economic shifts, and changes in social cohesion. Highway construction often displaces communities,

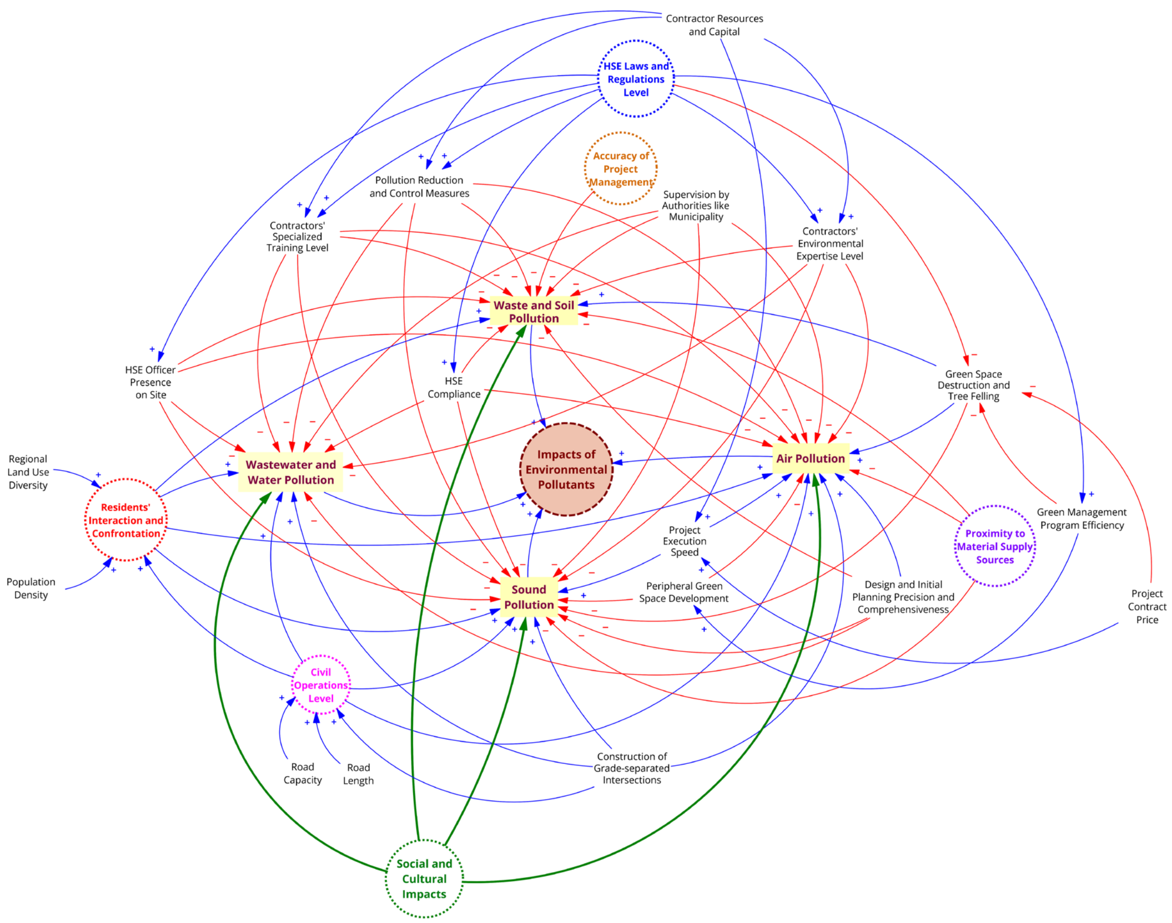

Fig. 4. CLD modeling of the environmental subsystem

affecting local economies and small businesses, which can increase unemployment and social inequality, leading to further disruptions and lasting demographic shifts.

The CLD also demonstrates how infrastructure projects transform the cultural landscape by altering physical layouts and access to landmarks, potentially eroding community identity and social capital. Environmental changes from construction, like noise and air pollution, impact social dynamics by straining services and altering lifestyles, prompting broader social shifts as communities adapt or relocate.

The CLD explores how construction factors like "Project Execution Speed" and "Contractor's Environmental Expertise" affect pollution. Faster execution can intensify short-term pollution, while shorter supply routes reduce transport emissions. This mapping enables stakeholders to evaluate each factor's effects and mitigation strategies for environmentally responsible urban development.

For simplification, intermediate variables connecting socio-cultural and environmental impacts have been omitted, resulting in a direct causal model. While this streamlines analysis, it may overlook nuanced feedback loops that enrich understanding.

The CLD of the Social and Cultural subsystem (Figure 5) combines empirical data, theory, and stakeholder input to capture urban social fabric dynamics impacted by construction. The model underscores the need for urban planning that considers both immediate and delayed

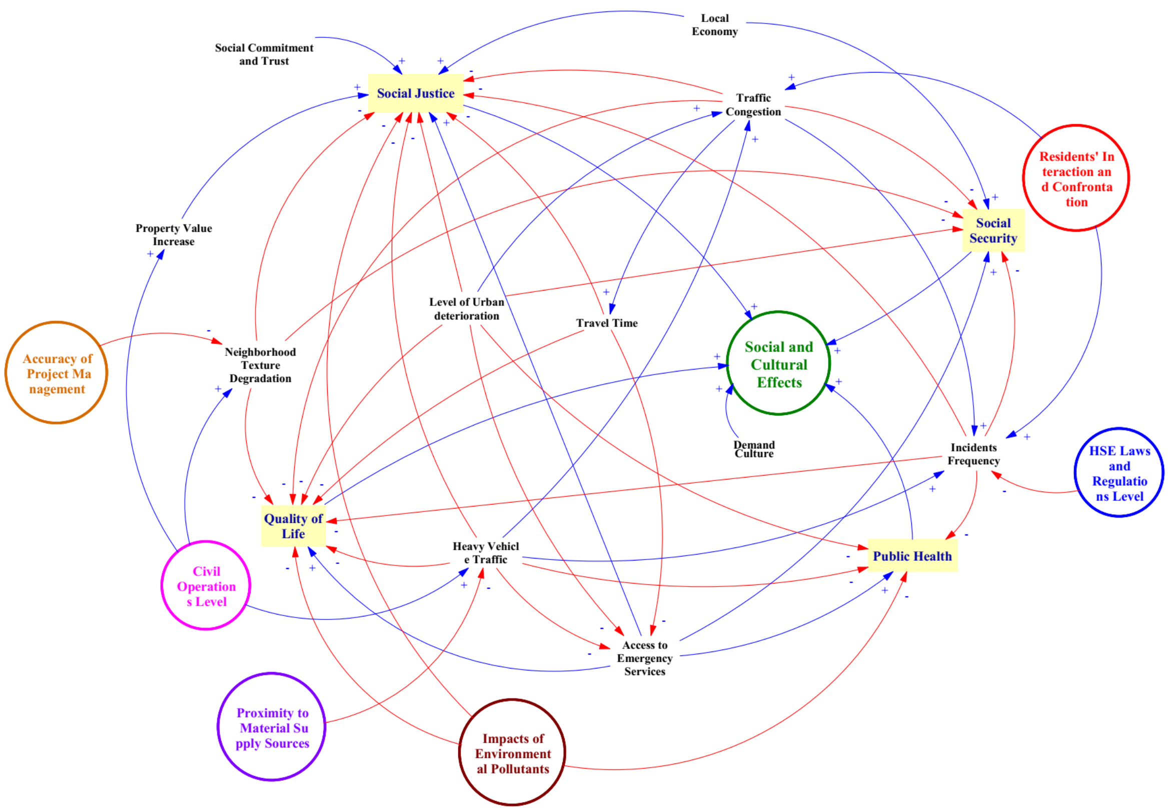

Fig. 5. CLD modeling of the social and cultural subsystem

social effects, aiming for infrastructure that sustains both the environment and community well-being. Central variables like “Residents’ Interaction and Confrontation” reflect community responses that can influence the construction process. Additionally, regulatory factors from the environmental subsystem impose constraints on maintaining social cohesion and cultural integrity. This CLD serves as a vital tool for policymakers and planners to devise culturally sensitive approaches to urban development challenges.

The Causal Loop Diagrams (CLDs) in this study reveal how urban highway construction impacts both environmental and social-cultural subsystems, highlighting the intertwined nature of pollution and social well-being. Environmental degradation, such as pollution, disrupts ecosystems and affects public health, potentially inciting public grievances and opposition. Shared variables like “Residents’ Interaction and Confrontation” underscore how increased pollution can lead to civil unrest, while factors such as “Proximity to Material Supply Sources” affect both environmental footprints and local socio-economic conditions. These interconnections show that changes in one subsystem create cascading effects in the other, emphasizing the need for integrated urban planning approaches.

Our findings provide essential guidance for urban planners and policymakers, suggesting strategies for sustainable development. Key recommendations include:

1. **Integrated Planning**: Highway projects should be designed holistically, factoring in both transportation benefits and potential disruptions. This calls for interdisciplinary collaboration among environmental scientists and social researchers.
2. **Environmental Management**: Implementing green practices, such as pollution control measures, helps minimize ecological footprints and enhances community health.
3. **Social Impact Assessment**: Comprehensive social assessments are necessary to preemptively address traffic and noise pollution impacts on social capital.
4. **Regulatory Frameworks**: Policies should be flexible and responsive to the evolving environmental and social dynamics identified in the CLDs.

Strategies like green infrastructure, low-emission machinery, and participatory planning help reduce environmental and social impacts. Enforcing Health, Safety, and Environment (HSE) standards, coupled with continuous environmental monitoring, enables timely responses to emerging issues.

This study bridges a critical gap by using CLDs to analyze the feedback between environmental degradation and social outcomes, providing a unified framework that previous studies have often addressed in isolation. While limitations exist, such as lack of systematic sampling and detailed pollutant analysis, our research offers actionable insights and encourages further exploration into integrated impact mitigation strategies for urban development projects.

CONCLUSION

This research provides a comprehensive examination of the environmental and social implications of urban highway construction in Tehran, employing Causal Loop Diagrams (CLDs) as a critical tool for understanding the complex interdependencies and feedback loops inherent in such projects. Our findings illuminate the multi-layered impacts that these developments exert on both environmental quality and social well-being, necessitating a shift from traditional planning approaches to a more integrated and holistic methodology.

The CLDs crafted during our study not only trace the immediate consequences of highway construction, such as increased air and noise pollution but also reveal how these factors contribute to broader socio-economic disturbances, including community displacement and alterations in the socio-cultural landscape. These environmental stressors pose substantial health risks and degrade natural habitats, while also precipitating socio-economic shifts that impact property values and public health.

In light of these insights, we advocate for an adaptive and proactive planning approach that integrates environmental management and robust community engagement to mitigate these adverse impacts. Our study suggests that effective urban planning must not only address the infrastructural needs but also prioritize environmental stewardship and social equity. This approach involves crafting regulatory frameworks that are responsive to the dynamic interactions identified in the CLDs, enabling policies that both mitigate and adapt to the evolving urban landscape.

Furthermore, the study acts as a foundational piece for ongoing research. Future studies should aim to refine and expand upon the models developed here by incorporating historical data and emerging trends. Such efforts will enhance our understanding and methodologies, ensuring that the progression of urban infrastructure remains in balance with environmental sustainability and the collective well-being of the community.

In addition to the theoretical contributions of this research, the findings offer valuable practical applications for both basic and management-level decision-making. From a basic application perspective, the Causal Loop Diagrams (CLD) developed in this study can serve as a template for analyzing the complex interactions between environmental and sociocultural factors in other urban infrastructure projects. Urban planners, environmental managers, and policymakers can use these models to identify critical feedback loops and potential points of intervention to mitigate negative impacts. On the management side, this research provides a framework for implementing more comprehensive environmental and social impact assessments (ESIA) that go beyond traditional methods. By integrating environmental management strategies with social engagement initiatives, stakeholders can make more informed decisions that balance infrastructure development with the preservation of community well-being. This approach encourages a proactive stance in minimizing long-term environmental damage while enhancing social resilience, making it particularly relevant for sustainable urban development projects.

Ultimately, our research underscores the need for policy reforms and innovative urban planning that prioritize the long-term health of both the city's ecosystem and its inhabitants. By striving for an equilibrium that fosters resilient and livable urban spaces, we can ensure that the expansion of urban infrastructure serves the needs of future generations without compromising environmental integrity and social harmony. This not only contributes to academic discourse but also provides a practical framework for sustainable urban development, aimed at creating environments that support both human and ecological well-being.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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