Developing Indicators for Comprehensive Evaluation of Equity in Transportation System

FINAL REPORT

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Disclaimer Statement

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16. Abstract This report studies the complex nature of equity within transportation systems, revealing its wide aspects and implications beyond simple access to mobility. Through an extensive literature review, the report underscores the interconnectedness of transportation equity with socioeconomic disparities, environmental sustainability, public health, traffic safety, and social cohesion. It discusses the challenges and barriers to achieving equitable transportation, as well as strategies for improvement and future directions for research. Practical insights were gained from interviews with professionals experienced in maintaining transportation equity, enriching the theoretical foundations with real-world applications. These discussions informed the development of a transportation equity assessment model and led to actionable recommendations and policy implications. The report introduces innovative methodologies for evaluating infrastructure equity, including an equity-based limit state function and agent-based equity modeling (ABEM), offering a new framework for assessing inequality and identifying areas for intervention. Emphasizing the importance of integrating equity considerations into transportation planning, this study argues for equity as a fundamental pillar in developing sustainable, efficient, and just transportation networks. It calls for future research to refine equity metrics, validate them with extensive datasets, and explore their implications for enhancing infrastructural equity. Collaborative efforts among experts, communities, and governments are highlighted as crucial for addressing disparities and advancing toward equitable transportation solutions.			
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CHAPTER 1: INTRODUCTION

Transportation equity has emerged as a critical area of focus within the field of transportation planning and policy. In recent years, concerns about social and environmental justice have underscored the need to examine and address the disparities in access, affordability, and quality of transportation services experienced by different communities. Due to inequitable transportation systems, marginalized communities, such as low-income individuals, people with disabilities, and minority groups, frequently have disproportionate burdens and hurdles to accessing basic services, employment opportunities, education, and healthcare. These inequities not only perpetuate social and economic disparities but also contribute to environmental degradation and hinder overall community well-being. Therefore, understanding and defining transportation equity have become imperative to promote inclusive and sustainable transportation systems.

The evolution of equity in transportation systems has unfolded over several decades, reflecting a growing recognition of the profound impact that transportation disparities have on society. Starting in the late 20th Century, the passage of the Civil Rights Act of 1964 and subsequent legislation highlighted the importance of equitable access to transportation as a fundamental right (*1*). In 1990, the Americans with Disabilities Act (ADA) was signed into law in the United States. It mandated that public transportation systems be made accessible to individuals with disabilities, ensuring that they have equal opportunities for transportation (*2*). In 1998, the Transportation Equity Act for the 21st Century (TEA-21) was enacted. It aimed to promote equity in transportation by allocating federal funds to address transportation disparities and improve accessibility in underserved communities. The 21st Century has witnessed a continued evolution in the understanding of transportation equity, with an increasing emphasis on the intersectionality of equity with environmental justice, public health, and sustainable development (*3*). Starting in the early 2000s, the emergence of shared mobility services, such as ride-hailing platforms like Uber and Lyft, has transformed the transportation landscape. Later, Vision Zero Initiative (2014-Present) was initiated; it recognizes the disproportionate impact of traffic-related incidents on marginalized communities and seeks to improve equity by prioritizing safety for all road users (*4*). Today, there is a growing consensus that equitable transportation systems should be designed and operated to address the diverse needs and experiences of communities. This ongoing evolution has prompted the integration of equity considerations into transportation planning and policy-making, with a focus on inclusive and participatory approaches. By striving for fairness, accessibility, and opportunity for all, the evolution of equity in transportation seeks to create a more just and sustainable future.

In this report, the research team aim to unpack transportation equity concept and comprehend its complex and interrelated aspects through three main approaches. First, the team completed a comprehensive literature review that composed of content analysis of the reviewed articles to explore the prevalent transportation-equity-related topics being discussed and studied in research. In addition, the study team conducted semi-structured interviews with professionals who has

experiences working on transportation equity; this approach aimed to identify takeaways from practical experience that could complement the theoretical findings from literature review to develop a methodology to evaluate equity in transportation systems. Lastly, the team developed an innovative evaluation model to assess transportation equity. The report is structured as follows: the second chapter presents the literature review, third chapter explores the interviewees understanding and experience with transportation equity, the fourth chapter discusses the development of an approach to evaluate transportation equity, and lastly, the fifth chapter concludes the findings of this study. The chapters from the second to the fourth include findings-based recommendations. The study will provide enriched input for policy-makers and practitioners to foster the development of more equitable and inclusive transportation policies, programs, and infrastructure investments.

CHAPTER 2: LITERATURE REVIEW

A considerable body of literature has emerged in recent years, addressing the several aspects of transportation equity. Researchers have examined various dimensions of equity, including spatial distribution of transportation resources, affordability of transportation services, accessibility to key destinations, and the impact of transportation decisions on disadvantaged communities. Studies have highlighted the disproportionate impacts of transportation inequities on vulnerable populations, such as low-income households, communities of color, and individuals with limited mobility options. Furthermore, the literature has explored the interplay between transportation equity, social determinants of health, and environmental justice, emphasizing the need for integrated approaches to address systemic inequalities. However, while the existing literature offers valuable insights into specific dimensions of transportation equity, there remains a need to synthesize and define the concept more comprehensively.

This chapter aims to build upon the current literature by providing a holistic understanding of transportation equity and identifying key factors and strategies for promoting equitable transportation systems. By critically examining the existing literature, synthesizing various perspectives, and identifying common themes and key elements, this review provides a clear and comprehensive understanding of the multidimensional aspects of transportation equity. Furthermore, it identifies emerging trends, innovative strategies, and promising practices that promote equity in transportation systems.

Sources Database and Search Design Strategy

Google Scholar and Scopus were utilized as the primary source databases. Google Scholar provides a wide range of scholarly publications, while Scopus is known for its inclusivity and robust search and analysis capabilities (*5*). To compile the required literature, this study employed a systematic search approach on Google Scholar. The search targeted recent literature published within the last five years (2019-2023). Selected documents were published in the English language, encompassing worldwide research articles and grey literature (i.e., academic papers, research and committee reports, government reports, and conference papers). “Transportation Equity” and “Transport Equity” were the major search terms. In Scopus, the search query was performed in titles using the selected documents from Google Scholar, and the Boolean operator OR was utilized to merge the various components of the search query.

The data search process uncovered over 6000 documents; to filter these initial results, a title, keywords, and highlight sections screening was performed, resulting in 642 relevant studies. Following the abstract screening, a full-text review was performed on 341 studies, and 92 documents were ultimately selected. **Figure 1** illustrates the selection process.

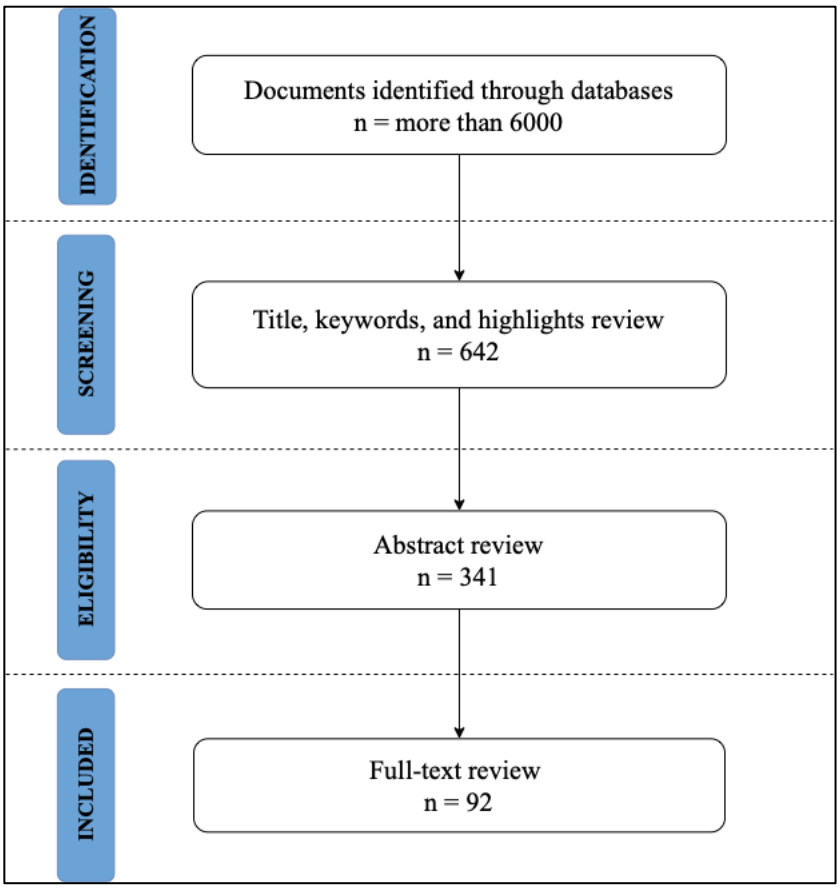


Figure 1 PRISMA flow diagram of literature review

The selected 92 documents are distributed in terms of the document type into 77;84% of research articles, 11;12% technical reports, and 4;4% academic papers (i.e., thesis and dissertations). In terms of country of origin, the majority of the documents are from the United States, accounting for 46;50% of the total documents, followed by China with 12;13%, documents from Europe accounted for 8;9%, Canada 6;7%, Latine America 5;5%, Australia 3;3%, and the rest 13% were distributed around other parts of the world, including India, Iran, Bangladesh, Japan, Sri Lanka, and Chile. Regarding the publication year, 32 documents were published in 2022; 25 in 2021; 20 in 2020; and 15 in each of the years 2019 and 2023.

The collected data were summarized and exported to Microsoft Excel for further analysis and assessment. The main information comprised titles, authors, year of publication, country, type of document, keywords, and abstracts. To uncover underlying patterns, highlight significant associations, and provide rich insights into the reviewed literature; the authors performed three types of qualitative analysis, given distribution analysis, co-occurrence analysis, and thematic analysis.

Qualitative Analysis – Content Analysis

The authors performed a distribution analysis of keywords frequencies to assess the content of published research works and demonstrate the core of literature in transportation equity. Word frequency analysis helps recognize the association and relationships between the ideas and concepts of various research works. The outcome was visually demonstrated using word clouds, where the size of each word is proportional to its frequency. Co-occurrence analysis involved examining the frequency and patterns of co-occurrence between terms or concepts in the abstracts of the selected documents, aiming to identify relationships and associations. This analysis provided insights into interconnectedness, thematic clusters, and key themes within the data (6). Co-occurrence analysis results were visualized using VOSviwer software (7), which uses clustering and mapping methods to establish words-network maps relying on the analysis results. Lastly, thematic analysis was performed to systematically identify and interpret themes within the qualitative data, offering a deeper understanding of the qualitative meaning and context (8). Thematic analysis was performed by implementing a Python script that applied Natural Language Processing (NLP) techniques, including tokenization, stop word removal, and TF-IDF vectorization. The script also leveraged Non-negative Matrix Factorization (NMF) to cluster these terms into distinct themes. Like the keyword distribution analysis, thematic analysis was visualized using word clouds for the generated themes. By employing these methods, the study gained a comprehensive understanding of both the quantitative associations and qualitative nuances within the dataset, enabling a robust exploration of the research topic.

The distribution analysis of keyword frequency revealed compelling insights into the prominence of various terms within the abstracts of the research articles. Common terms, including transportation, equity, and transport, were removed. Results were visualized using word cloud, which demonstrated a varied distribution, with some keywords exhibiting significantly higher frequencies than others (**Figure 2**). Notably, certain keywords related to accessibility, mobility, and planning emerged as key focal points in the literature, indicating their prevalence and importance in transportation equity. Conversely, other terms showed lower frequencies, suggesting their relative underrepresentation or limited emphasis in the examined literature, such as congestion and structure.

Figure 2 Word cloud of the selected documents' keywords

Co-occurrence analysis of terms in the abstracts was performed with a minimum number of occurrences of a term set as 10. Of the 3849 terms, 98 met the proposed threshold. The authors adopted a relevance score of 60%; accordingly, 61 terms were selected as the most relevant. The most occurrence term after excluding *transportation equity* and its related terms was city; 87 occurrences. The term community follows with 53 occurrences, distribution; 51 occurrences, public transport; 43 occurrences, plan; 41 occurrences, cost; 39 occurrences, and mobility; 39 occurrences. The map categorized the terms into four clusters (**Figure 3**). These clusters can be classified as follows: cluster 1, red color, represents an emphasis on the practicalities and individual impact of transportation equity. It showcases the nuanced elements of transportation, particularly relating to personal usage, socio-economic implications, and mobility patterns. The presence of terms like car, public transit, job, and destination suggests a focus on the role of transportation in daily life, employment access, and movement to various destinations. The frequency of words like disadvantaged group, cost, and quality indicates the effect of socio-economic aspects, affordability, and the quality of transportation service on user experiences. Cluster 2, green color, concentrates on the systemic and policy-related elements of transportation equity. This cluster's context revolves around decision-making processes, community-centric planning, and the barriers and challenges faced in achieving equitable transportation. Terms like approach, plan, and decision imply discussions on methods and strategic planning aimed at realizing transportation equity. The mention of community and work indicates the involvement of community engagement and collective efforts in this process. Also, the term COVID suggests an exploration of the impacts of recent global events on transportation equity. Cluster 3, blue color, has a strong urban context, revolving around city-specific mobility solutions and their usability. With terms like city, bike, e-scooter, rider, and user, this cluster suggests an exploration of micro-

mobility options like bicycles and electric scooters within urban settings. Time and travel time underscores the importance of efficiency in urban mobility. Words like methodology and lack inquire into the shortcomings in current urban mobility systems and the methods to study them. Cluster 4, yellow color, appears to cover broader societal and global aspects of transportation equity. It suggests an examination of how societal factors and geographical context influence transport equity. The terms China, country, public transport, mobility, transport equity, and transport system hint towards studies of transport systems at a national or regional level. Furthermore, the inclusion of terms like disability signifies the focus on inclusivity, ensuring transportation systems serve all societal segments. The word distribution could refer to the spatial distribution of transport services or the distribution of accessibility across different population groups.

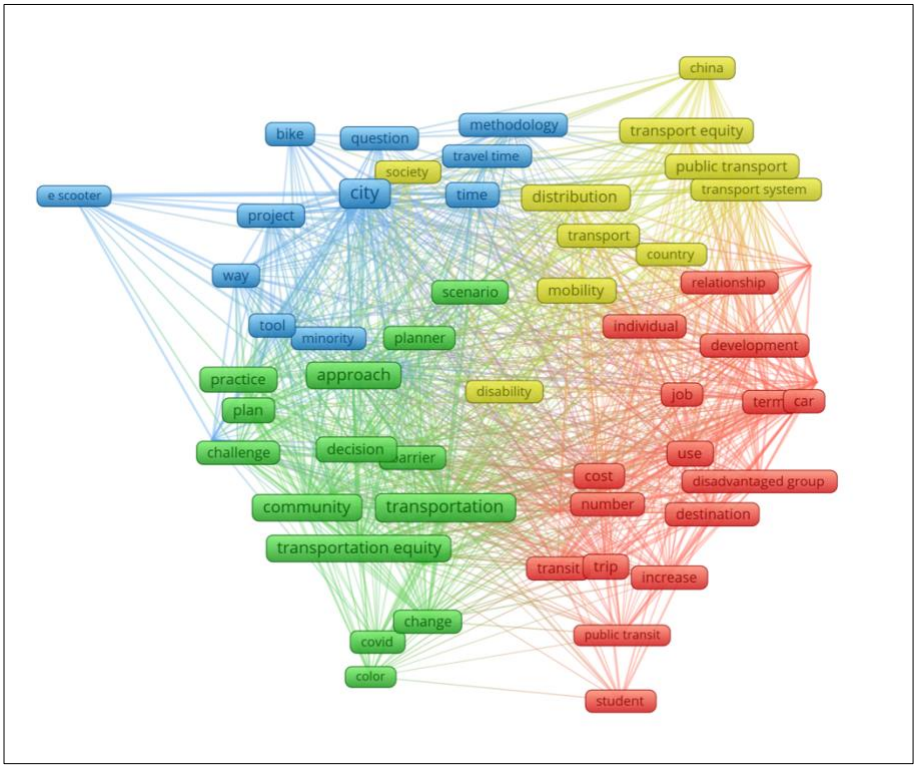


Figure 3 Network visualization map for co-occurrence analysis of terms in the reviewed documents' abstracts

Thematic analysis was performed over the abstracts of the selected documents; analysis results grouped the most frequent words into themes based on their frequency of appearing together in one context. Five main themes were produced, indicating the major topics addressed by the analyzed abstracts, and providing a comprehensive insight into the issues and discourses of transportation equity (**Figure 4**). The first theme (Theme 1) highlights *Public Accessibility and Urban Development*, the associated words with the theme point toward challenges and solutions related to providing equitable transportation opportunities in urban areas. The theme focuses on social and spatial aspects of urban development, underscoring the importance of public facilities and income distribution. The second theme pertains to *Planning and Research in Transportation*

Equity and indicates the importance of transportation plans and their role in health and social justice. The third theme underscores *Rural Mobility and Income Accessibility*; the terms presented in the theme's word cloud indicate discussions on the transportation needs and accessibility challenges of low-income, rural areas. In addition, the theme highlights the emergence of new mobility options (e.g., e-scooters) as a potential solution to improve mobility. The fourth theme revolves around *Bike Sharing and Travel Safety* and focuses on bike-sharing models, their risks, safety issues, and optimization, which underlines the importance of perceived safety and risk factors in the context of transportation equity. Lastly, the final theme, *Transit Services and Fare Policies*, indicates debates around the affordability and accessibility of various transit services, fare policies, and their impact on riders.

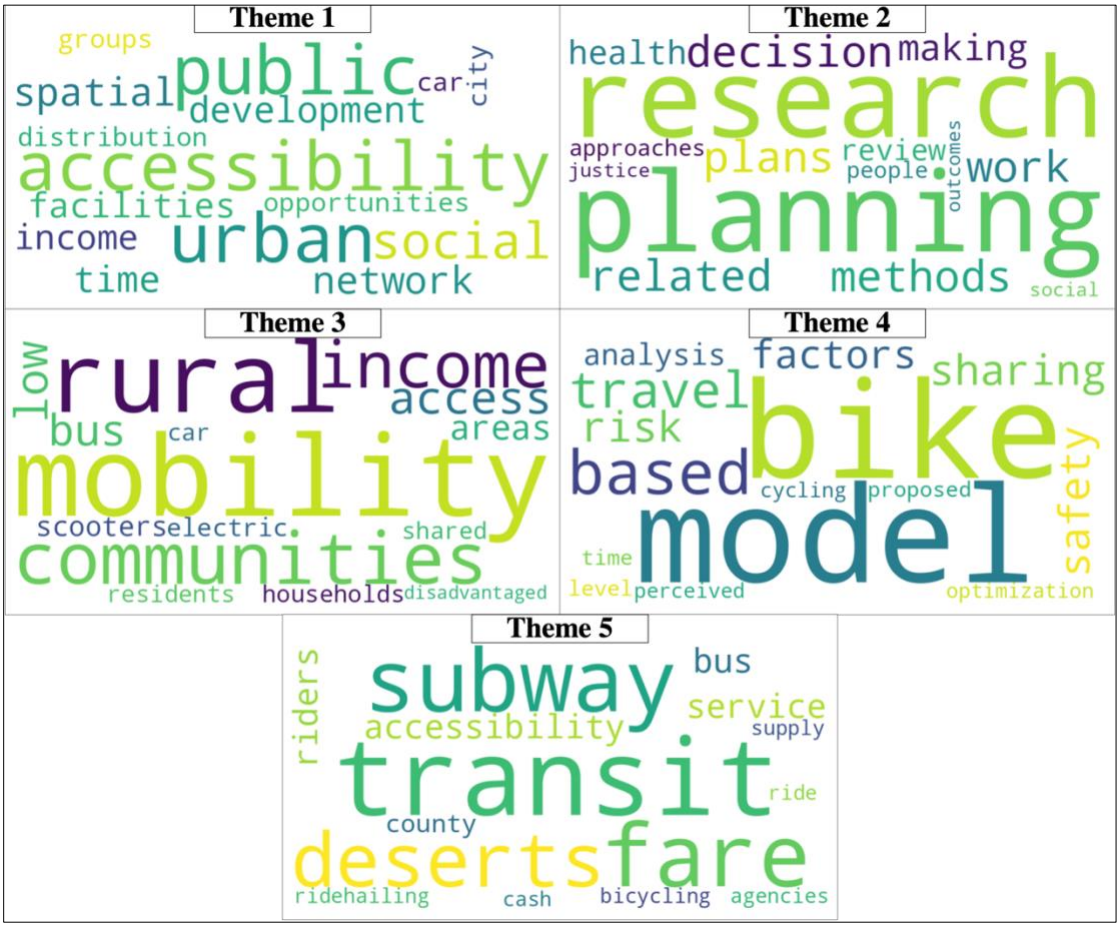


Figure 4 Word clouds for the generated themes

Discussion

Results from the keywords distribution analysis, co-occurrence analysis clusters, and thematic examination of the abstracts contributed to a thorough comprehension of transportation equity. This section synthesizes these findings and sheds light on the current state of equity in transportation systems in the existing literature; it also summarizes the challenges and solutions that are proposed or considered; and proposes potential directions for future research.

Defining Equity in Transportation Systems

Referring to the analysis results and the reviewed literature, equitable transportation is primarily portrayed as the provision of fair and accessible mobility services to all societal groups, with a prominent emphasis on supporting disadvantaged and low-income individuals, particularly in urban contexts, where access to public transit is crucial for socio-economic opportunities (*9–17*). Transportation equity was also found to extend to policy-making, planning, and developmental practices. These elements underscore the systemic nature of equity, requiring the integration of fair practices into strategic decision-making and resource allocation processes to ensure comprehensive accessibility and inclusivity in both, the short and long terms (*17*). In addition, the findings underline the diverse modal considerations within the transportation equity discourse, which is not limited to any specific mode of transport; it includes private cars, public transit, bikes, walking, and emerging mobility solutions, such as e-scooters (*9*,*15*,*18–29*). Furthermore, many researchers and practitioners referred to the fair distribution of burdens and benefits as a crucial aspect of transportation equity (*30*–31). The comprehensive view of equity resonates with extant research, confirming that equity must encompass all facets of transportation to effectively address disparities and foster a more inclusive mobility landscape.

Challenges and Barriers to Achieving Transportation Equity

To comprehend the complexities of equity in transportation systems, it is significant to understand the various challenges that hinder achieving truly equitable transportation systems. In light of the analysis results and in conjunction with the existing literature, this section demonstrates these restrictions. First, as evidenced by keyword distribution, *Public Accessibility and Urban Development* themes (Theme 1), and Cluster 1, the inequitable distribution of resources and services appears as a significant concern. The terms accessibility, public urban, network, and development are notably prevalent, pointing to the disparities in access to transportation facilities among different social groups, often between urban and rural or low-income communities. Existing literature affirms this, highlighting how variations in socioeconomic conditions (*9–32*), geographical locations (*13–14*, *16*, *18*, *20*, *22–23*, *25*, *29*, *31*, *33–39*), and accessibility (*12*, *20*, *26*, *29*, *31–32*, *40–47*) can exacerbate inequity in transportation systems. Barriers related to planning and decision-making processes are underscored in the *Planning and Research in Transportation Equity* theme (Theme 2) and Cluster 2, where terms like planning, decision, and approach frequently occur. Many times, equity considerations are not adequately integrated into these processes, leading to outcomes that may disproportionately affect disadvantaged groups. Literature corroborates this, revealing a consistent pattern of inequitable transportation planning and inadequate consideration of equity in decision-making practices. Furthermore, the emergence of new technologies such as shared-mobility services (e.g., bike-sharing, and e-scooters), as indicated in the fourth theme and Cluster 3, while enhancing mobility options, also present unique challenges. These include issues of affordability, accessibility, and safety, which could worsen existing inequities if not adequately addressed. Current literature also expresses concerns about

the risk of these new mobility options being concentrated in already well-served urban areas. The defined challenges and barriers are the foundation for formulating effective strategies and solutions to mitigate these issues in the future.

The Barriers Associated with Transportation Inequity

The obstacles to transportation equity are multifaceted, addressing various areas that extend beyond the mere availability and accessibility of transportation services. The equity of access to critical services such as education, healthcare, employment, and other essential destinations is deeply tied to this broader discussion (*18*, *39*, *48–52*). From the educational equity aspect, public transit options in rural areas or low-income communities may not reach schools or universities, or schedules may not align with schooling hours. This could highly limit the opportunities for students to gain education and, thus, perpetuate socioeconomic inequities. Current literature discussed this issue, Sun et al., (*53*) examined the opportunity of students to attend self-improvement activities and performed a comparative analysis between students in urban campuses and the ones in sub-urban areas; the authors highlighted that students in sub-urban campuses are disadvantaged regarding the educational opportunities and access to transportation. Other studies highlighted that people who live in rural areas or low-income communities have lower access to transportation, which reduces their educational opportunities (*12*, *18*, *54*). In addition, Weinstein et al. (*55*) pointed out that equity in transportation access is an essential component of educational equity; the authors examined equity in transportation finance and bus provision and found significant racial and ethnic disparities. Several researchers discussed the importance of addressing issues to access education and tackle transportation inequity; for instance, Bierbaum et al. (*56*) adopted a mobility justice framework and provided guidelines that can help integrate education and transportation planning. Alongside, other studies highlighted that accounting for equity in promoting specific travel modes to school, such as walking, is crucial (*57*).

Similarly, access to healthcare is also influenced by transportation equity (*36*, *42*, *51*, *58–59*). Individuals without reliable transportation often experience difficulty in reaching healthcare facilities for routine check-ups, emergency visits, or ongoing treatments. This is especially true for individuals who are older (*60*), disabled (*60*), or live in remote areas (*42*), as these groups typically have fewer options for personal transportation and may be more dependent on public transit (*36*, *61*). In addition, current studies pointed to low-income groups, people of color, and minorities, as highly vulnerable populations to transportation inequity in their healthcare accessibility (*36*, *62*). When transportation to healthcare facilities is unreliable or inaccessible, health outcomes can be negatively impacted, leading to further inequities. Moreover, in the cases of critical situations, such as the COVID-19 pandemic that spread worldwide in 2020, the health impacts of transportation inequities could be highly exaggerated (*63*). Furthermore, a community's overall public health condition could be affected by the level of considering equity in their multi-modal transportation planning; Wu et al. (*59*) argued that despite the positive health outcomes of active transportation modes (i.e., walking and biking), if equity is not considered in their associated plans, they could affect the risk of traffic injury or increase exposure to air pollution.

In the realm of employment, job accessibility is heavily impacted by transportation equity (*16*, *18*, *31*, *47*, *49*, *51–52*, *64–65*). Without reliable and affordable transportation options, accessing jobs, especially those that are not located in the immediate vicinity of one's residence, becomes a challenge. This issue is compounded in areas where housing affordability and job availability do not overlap, forcing individuals to choose between affordable housing and proximity to potential jobs, as mentioned by Guo et al. (*14*). Disadvantaged groups, including low-income communities (*14*, *24*, *65*), older and disabled populations (*64*), women (*64*), and people of color (*66*), were found to be greatly affected by transportation inequity to access job opportunities.

Lastly, access to other essential destinations, such as grocery stores, community centers, libraries, parks, and government agencies, is an integral part of transportation equity (*12*, *32*, *39*, *49*, *51*). The ability to reach these places directly impacts an individual's quality of life, including their ability to access fresh food, engage in community activities, and utilize essential services. This is especially true for individuals with disabilities and older adults (*32*). Each of the aforementioned aspects plays a significant role in shaping the lived experiences of individuals and communities, making it essential to address these barriers in the pursuit of transportation equity.

Strategies to Enhance Transportation Equity

The literature identified various strategies and opportunities to enhance transportation equity, which could work as proposed solutions to the discussed challenges and barriers. Several studies reveal that planning methodologies play a crucial role in enhancing transportation equity. Notably, incorporating comprehensive and diverse community input in decision-making processes helps ensure that the needs of traditionally marginalized groups are considered (*67–70*). This is best exemplified in our analysis of the *Planning* theme, where terms like work, related decision, methods, making, and review indicate the importance of comprehensive, diverse, and participatory planning processes. Handful literature emphasized the corporation between planning and equity (*15*, *25*, *27*, *34*, *71–75*), Ryerson et al. (*15*) discussed equity-driven planning typologies using accessibility and individual constraints to guide transportation investments. In addition, Litman (*71*) highlighted that transportation planning decisions have significant equity impacts.

Additionally, the prominence of terms like bike-sharing, e-scooters, and public transit indicates that technology can be an enabler of transportation equity; shared and electric mobility can provide affordable and accessible transport services. Nonetheless, the presence of barriers and low-income in the same themes indicates that these solutions should be implemented cautiously, ensuring access to all population groups regardless of income levels (*37*, *46*, *76–83*).

Strategic investments in public transit, particularly in rural and underserved areas, is another major theme across the literature. By increasing the quality, frequency, and reach of public transit, transportation equity can be significantly enhanced. This is underscored by the prominence of terms like rural, bus, and mobility in the third theme (*9*, *21*, *29*, 43, *47*, *49*, *67–68, 70*, *84–92*).

Furthermore, the literature acknowledges the importance of policy and regulation in transportation equity. For instance, policies that prioritize access over mobility can profoundly affect equitable transportation systems. The performed co-occurrence analysis indicated the relevance of the terms of policy and regulations in achieving transportation equity (*74*, *79*, *93–94*).

This section presents that enhancing transportation equity needs a multifaceted and integrated approach that includes inclusive planning, strategic investments, technological advancements, and appropriate policy framework.

A Case for Holistic Approach to Transportation Equity

The analysis results point out that the breadth and complexity of issues surrounding transportation equity necessitate adopting a holistic approach to transportation equity. This is echoed by the review of existing literature, which highlights the need for multi-dimensional solutions. The emergence of themes such as accessibility, spatial distribution, and planning in the thematic analysis underpins the multifaceted nature of transportation equity. Nevertheless, it involves other considerations, such as urban design, social factors, economic factors, and policy-making. These findings align with several current research efforts (*20*, *96–101*), which underscores the interplay between transport, land use, and social factors in determining transportation equity. The recurrence of terms such as barrier, challenge, and decision highlight the multitude of obstacles that must be overcome.

The term holistic approach also implies inclusivity in decision-making processes. The importance of incorporating community voices and addressing their specific concerns is evident from the high occurrence of terms such as community, decision, and plan in the co-occurrence analysis. This echoes the sentiments of scholars (*67–70*), who argue that achieving equity in transportation systems necessitates community-oriented planning and engagement. Moreover, the adoption of sustainable modes of transport like biking, as suggested by the thematic analysis, to the potential of emerging technologies captured in the co-occurrence clusters, these opportunities require a broad, systemic perspective to fully capitalize on. The suggested holistic approach involves mobilizing various elements together, including policy, planning, technology, community engagement, to create equitable and inclusive transportation systems (*20, 101, 103–106*).

Future Directions for Transportation Equity Research

The need for a more comprehensive and nuanced understanding of transportation equity is a recurrent theme in the findings that suggests a potential direction for future studies. This could encompass more intersectional research, examining how different aspects of identity, such as age, race, gender, or socioeconomic status, interact with transportation equity and develop scenario-based equity frameworks.

Future research could also investigate deeper into the identified challenges and barriers associated with equitable transportation. While this study provides a broad understanding of these barriers, such as income disparities, urban-rural differences, and access to jobs, more focused

empirical studies can illuminate specific mechanisms and impacts. In addition, comparative studies across different geographical contexts (e.g., rural, and urban areas) could offer valuable insights into how local contexts shape transportation equity. In terms of the planning and decision-making aspects, more efficient approaches to incorporate equity principles into transportation planning and policy-making processes are needed. This could include enhancing community engagement and having the voice of traditionally underserved groups heard. Regarding emphasizing an equitable emergence of new technologies in transportation, efforts are still needed in their equity implications, including their accessibility, affordability, and impacts on existing transportation systems. Lastly, a promising direction for future research is the evaluation of strategies and interventions aimed at enhancing transportation equity. This could be achieved by performing empirical studies assessing their effectiveness and scalability could significantly contribute to the body of knowledge and practice.

Summary

This chapter provided a comprehensive examination of the complex concept of equity in transportation systems. The analysis illuminated diverse perspectives and definitions surrounding equity, showcasing its complex nature. Through the literature synthesis, it is evident that equity in transportation extends beyond the mere provision of equal access to mobility services. Instead, it encompasses a broad range of interrelated factors, including but not limited to socioeconomic disparities, environmental sustainability, public health, traffic safety, and social cohesion, which highlighted the need for a holistic approach to addressing transportation equity.

The significance of understanding and promoting equity in transportation cannot be overstated. A just and inclusive transportation system contributes to enhanced overall accessibility, economic opportunities, and quality of life for all individuals, particularly vulnerable and marginalized populations. Moreover, equitable transportation fosters social justice and reinforces the principles of fairness and equal opportunity. As the world continues to face urbanization, technological advancements, and combat climate change, it becomes increasingly imperative for policy-makers, planners, and stakeholders to prioritize equity as a fundamental pillar in shaping transportation systems. By incorporating equity considerations into policy development, infrastructure investments, and decision-making processes, cities can pave a path toward more sustainable, efficient, and people-centric transportation networks. Nevertheless, challenges lie ahead, necessitating ongoing research and collaboration among experts, communities, and governments. Future studies should focus on equity metrics, quantifying disparities and identifying vulnerable groups to tailor targeted interventions. Additionally, exploring the role of emerging technologies, such as autonomous vehicles and ride-sharing platforms, in shaping equitable transportation landscapes warrants attention.

CHAPTER 3: PRACTICAL INSIGHTS

To gain in-depth learning about an expert's experience, expertise, and co-produced insights related to an identified study topic, researchers utilized the interview approach (*107*, *108*). As a part of this research, the team conducted semi-structured interviews with selected transportation professionals and summarized the outcomes of the collected data. This approach aimed to explore the professionals' experiences with respect to their contribution to transportation equity, and identify key lessons learned from the anecdotal experience of the interviewees.

This chapter advances the opportunity to understand the responsible officials' insights and the real-life challenges they face in comprehending and maintaining transportation equity. To this end, the interview questions were semi-structured to cover focus areas concerning the following:

- The optimal goals of equity in transportation systems
- The evolution of transportation equity understanding over time
- Performance indicators of transportation equity
- The definitions of transportation equity

The interviews were semi-structured and consisted of ten questions, one fixed question on the interviewee's professional role/title and his/her experience, the remaining nine were flexible based on the interviewees' background. The research team interviewed 16 participants from 16 distinct organizations. The participating organizations were recruited purposively, sampling method was mixed between judgment (parties implemented programs or plans to maintain equity in transportation systems) and convenience (a total of 37 were selected as potential interviewees out of which 16 responded back and consented to participate in the study). The participated parties were distributed over 11 states. **Table 1** presents a summary of interviewees' affiliations and experience.

Table 1 Summary of Interviewees' Affiliation and Experience

State	Position	Affiliation	Years of Experience (complete)	Years of experience in current position
California	Researcher	Academic Institution	21	21
California	Researcher	Academic Institution	3	3
Colorado	Sustainable Transportation Director	Non-profit organization	7	5
Delaware	Transportation Planner	Public (Metropolitan Planning Organization)	18	13
Florida	Researcher	Academic Institution	5	5

State	Position	Affiliation	Years of Experience (complete)	Years of experience in current position
Minnesota	Transportation Planner	Public (Minnesota Department of Transportation)	8	3
Pennsylvania	Civil Engineer	Public (Philadelphia Department of Aviation)	19	19
Pennsylvania/New Jersey	Manager	Public (Delaware Valley Regional Planning Commission)	8	8
Texas	Director	Public (City of Huston)	23	3
Texas	Researcher	Academic Institution	3	3
Texas	Researcher	Academic Institution	3	3
Utah	Transportation Planner	Public (Utah Department of Transportation)	25	10
Washington	Deputy Director	Public (Washington State Department of Transportation)	23	18
Wisconsin	Transportation Planner	Public (Metropolitan Planning Organization)	10	6
National Program	Transportation Planner	Public corporation	36	9
National Program	Equity and Transportation Management Manager	Public (FHWA)	4	4

The interview design allowed the interviewees to reflect on the questions and share information that otherwise would have been missed. Participants were allowed to digress and probing questions, which allowed building on some not planned arose issues and allowed examples to be given; this offered a clearer and more detailed response from the participant. The interviews were conducted one-to-one, through the online platforms WebEx (*109*) and Microsoft Teams (*110*) with a duration of approximately an hour on average. Dialogues were audio-recorded and transcripted verbatim for further analysis. The research team coded the transcripts based on the defined four aspects, and exemplified the different levels, facets, and angles to unveil conclusions and lessons learned relevant to the identified goals of the interview. The results of this analysis are subsequently presented in the following section.

Findings

The summary of the interviews is discussed based on the predefined four aspects that shapes the landscape of equity in transportation systems. These encompass: the optimal goals of equity in transportation systems; the dynamic trajectory of how understanding around transportation equity has matured and shifted over time; key performance indicators that stakeholders employ to assess and drive equity in transportation; and the nuanced definitions of transportation equity as articulated by participants. This synthesis aims to map out the current landscape and identify the key factors and the metrics of success to guide future endeavors towards more equitable transportation system. Each theme is presented to provide a holistic understanding of the challenges and opportunities within the realm of transportation equity, supported by the firsthand experiences and insights of those deeply embedded in the field. This chapter will conclude with recommendations and policy implications, providing a clear direction for actions to advance equity in transportation systems globally.

Optimal Goal of Equity in Transportation Systems

In pursuit of an equitable transportation system, it is essential to define the optimal goals that address historical injustices, prioritize the needs of underserved communities, and foster collaboration with diverse stakeholders. Various perspectives on the goals and dimensions of transportation equity were explored and discussed by the participants from the field. The discussions around the optimal goals of transportation equity encompass a diverse array of perspectives, each emphasizing key principles for creating a fair, inclusive, and community-centric transportation system.

Community-Centric Planning and Inclusion

Several interviewees stress the importance of engaging with and prioritizing the needs of historically underserved or excluded communities in transportation planning, design, and construction. This involves ensuring that all aspects of transportation, including planning, design, and construction, inclusively reflect and serve the surrounding communities. The goal is to bridge the gap between project conception and implementation, ensuring projects are inclusive and meet the contemporary needs of the community from the outset.

Equitable Access and Distribution

Participants also highlight the critical need for equitable distribution of resources and access within transportation systems. This includes prioritizing safety, reliability, and accessibility for all individuals, particularly those in historically underserved groups. Ensuring that limited funding reaches the most underserved groups is emphasized, focusing on creating a system that benefits all segments of society and uplifts the entire system through equitable distribution and access in transportation planning and funding.

Safety, Reliability, and Comprehensive Equity Measures

Another perspective underscores the importance of safety, reliability, and implementing comprehensive equity measures within transportation planning and projects. This includes

interpreting and applying federal regulations with a broader vision of equity, developing guidance for incorporating equity into planning frameworks, and enhancing community impact assessments.

The three aspects of safety, reliability, and accessibility were mentioned by the majority of interviewees. Regarding safety, transportation equity ensures the safety of all individuals by implementing measures to reduce traffic fatalities and injuries, particularly in underserved communities. This involves enhancing pedestrian and bicycle safety through infrastructure improvements such as crosswalks, sidewalks, bike lanes, and traffic calming measures. Additionally, safety initiatives include addressing systemic issues like traffic enforcement disparities and inadequate street lighting in historically marginalized areas. In terms of reliability, it means ensuring that transportation services are dependable and accessible to all individuals, especially those in underserved communities. This involves improving the reliability of public transit systems by increasing service frequency, expanding coverage to underserved areas, and implementing real-time information systems to reduce wait times and uncertainty. Moreover, equitable transportation planning considers the reliability of alternative modes of transportation, such as walking and cycling, by investing in infrastructure upgrades and creating interconnected networks that provide reliable travel options for all individuals, regardless of their socioeconomic status or ability. Lastly, transportation equity prioritizes accessibility by removing barriers to transportation and ensuring that all individuals have equal access to transportation options. This includes designing transportation infrastructure and vehicles to accommodate individuals with disabilities, such as wheelchair-accessible buses and tactile paving at transit stations. Additionally, equitable transportation planning involves improving access to transportation services for low-income and marginalized communities by reducing transit fares, providing subsidies for transportation costs, and enhancing connectivity between residential areas and key destinations such as schools, workplaces, and healthcare facilities. Participants highlighted that by taking into account these three elements, transportation equity should aim to ensure that everyone, regardless of age, income, or ability, can access transportation options that meet their needs and allow them to participate fully in society; and can travel safely, regardless of their mode of transportation or background.

The Evolution of Transportation Equity Understanding Over Time

The evolution of transportation equity understanding over time reflects a dynamic shift towards more inclusive and equitable transportation systems, influenced by societal and political changes, technological advancements, and a deeper recognition of diverse community needs. Majority of participants highlighted that the murder of George Floyd in 2020 and subsequent societal awakening have significantly propelled this shift, highlighting the necessity for equitable outcomes in transportation. Federal initiatives, emphasizing investments in historically underserved communities, alongside the integration of diversity, equity, and inclusion (DEI) principles, have been critical in shaping current approaches to transportation equity.

Moreover, the adoption of new technologies and strategies, such as e-bikes and digital accessibility initiatives, alongside traditional infrastructure improvements, illustrates the evolving toolkit for addressing transportation equity. These approaches are complemented by rigorous public involvement strategies, emphasizing the need for personalized outreach and engagement with diverse communities to truly understand and address their unique transportation needs.

The discussions and narratives from various interviewees across different sectors of transportation—from urban planning to aviation—underscore the multifaceted nature of transportation equity. These perspectives illuminate the importance of considering social determinants of health, demographic data, and the specific needs of underserved communities, and emphasized that these aspects have been persistent over time in transportation equity context.

The cumulative insights from these interviews highlight a trend towards data-informed decision-making, community-driven planning, and the prioritization of safety, accessibility, and sustainability. As transportation equity continues to evolve, it is clear that a collaborative, informed, and context-sensitive approach is essential for creating transportation systems that meet the varied needs of different community sectors and contribute to a more equitable and just society.

Indicator Measures

The evaluation of equity in transportation systems is pivotal for ensuring that these systems serve all community members fairly and efficiently. Performance indicators play a crucial role in this evaluation, offering measurable insights into the effectiveness of transportation equity initiatives. Several interviewees have identified key performance indicators for evaluating transportation equity. These include:

Public Health and Safety

The social determinants of health and fatalities disaggregated by race, income, and ability are crucial for assessing the broader impacts of transportation on community well-being. These indicators highlight how transportation infrastructure and policies can affect health outcomes and safety for different demographic groups, underlining the need for equitable transportation solutions that prioritize the safety and health of all individuals, especially those in underserved communities.

Demographic and Spatial Accessibility

The demographic profile of mobile users and the spatial distribution of locations served delve into who is using the transportation system and how services are distributed across communities. By examining these factors, stakeholders can assess whether transportation services are inclusive and equitably accessible to diverse populations, including marginalized and historically underserved groups. This focus ensures that transportation planning and policies are designed to meet the unique needs of all community segments.

Economic Implications

The socioeconomic data related to transportation expenses explore the relationship between transportation access and economic burdens on families. This indicator sheds light on the affordability of transportation options and their impact on the financial well-being of individuals and families, particularly those with lower incomes. It emphasizes the importance of developing affordable and economically sustainable transportation solutions that do not disproportionately burden any single group.

However, not all interviewees chose to specify top performance indicators, highlighting a broader, more holistic approach to evaluating transportation equity. Discussions focused on broader themes such as diversity in business engagements, the alignment of funding with community needs, and the effectiveness of community engagement. This approach suggests that quantitative measures alone may not capture the full spectrum of equity considerations and that a comprehensive evaluation should also consider qualitative feedback and the overall impact of transportation projects on diverse communities.

In conclusion, while specific performance indicators offer valuable insights into the equity of transportation systems, the discussions underscore the complexity of transportation equity. A comprehensive evaluation approach that includes both quantitative metrics and qualitative assessments is essential for understanding and addressing the diverse needs of all community members. **Figure 5** below presents the indicator measures discussed by the participants; the indicators are orders based on their frequency among the participants discussion. Notably, safety was the most discussed one, whereas the indicators at the bottom of the pyramid are the least mentioned.

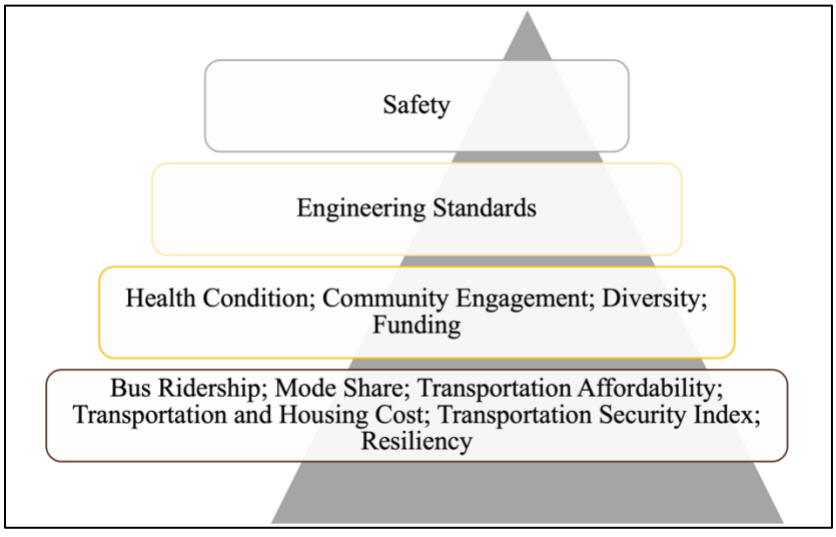


Figure 5 Indicator measures to evaluate transportation equity - defined by interviewees

Definition of Transportation Equity

The importance of a structured definition of transportation equity lies in its ability to guide policy and practice towards systems that serve all community members fairly. This requires a comprehensive approach that considers the various dimensions of equity, from accessibility and inclusivity to the distribution of benefits and burdens.

Interviewees have provided diverse perspectives on what constitutes an equitable transportation system. Key themes include the necessity for community engagement, especially with historically underserved groups, and the requirement for systems to be inclusive and reflective of community needs throughout all phases of planning, design, and construction. These definitions emphasize the importance of moving beyond access to ensure transportation services meet the specific needs of marginalized communities, suggesting a shift from car-centric models to more diversified mobility options that include walking, biking, and public transit.

Furthermore, the definitions highlight the role of safety, reliability, and accessibility for all users, challenging traditional biases and advocating for investments that support a broad spectrum of mobility needs. Participants also underscored the significance of integrating equity into planning processes, ensuring that transportation systems are developed with the input and for the benefit of all community members.

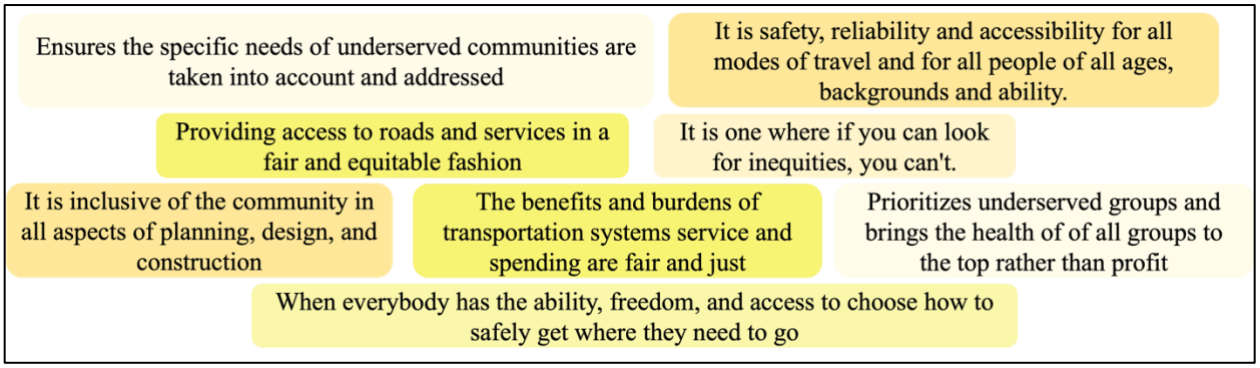


Figure 6 Transportation equity definition - quotes from interviewees

Conclusively, these insights reveal that an equitable transportation system is complex, requiring a commitment to inclusivity, safety, and community engagement. It must challenge existing paradigms and be designed with the holistic needs of the community in mind, ensuring that transportation equity is achieved through deliberate, informed, and inclusive decision-making processes.

Summary

Interviewees emphasized the necessity for meaningful community engagement, particularly with historically underserved and marginalized groups, in shaping transportation policies and projects. They highlighted the importance of listening to and acting on community feedback to ensure that transportation systems serve all community members equitably.

Additionally, interviewees advocated for diversifying mobility options and investing in infrastructure and services that support alternative modes of transportation, such as walking, biking, and public transit. They stressed the need to prioritize safety and accessibility for all users, particularly pedestrians and bicyclists, and to ensure that transportation systems are accessible to individuals of all ages, backgrounds, and abilities.

Furthermore, interviewees underscored the importance of integrating equity into planning frameworks and addressing historical disparities in transportation investment and infrastructure development. They emphasized the need for policies that explicitly target the transportation needs of historically marginalized communities and foster partnerships and collaboration among stakeholders to advance transportation equity goals.

Based on these findings, several recommendations and policy implications can be drawn to promote transportation equity:

Recommendations

Diversity and Inclusion

- Ensuring representation from diverse communities in decision-making bodies and project teams.
- Implement policies and practices that foster diversity and inclusion within transportation agencies and organizations, including recruitment and hiring practices that prioritize diversity and the creation of inclusive work environments.
- Incorporate equity and diversity training for transportation professionals to raise awareness of the unique needs and perspectives of marginalized communities and promote culturally competent approaches to transportation planning and service delivery.

Engage the community in decision-making processes, especially marginalized groups

- Engagement should be throughout all phases of transportation planning, from project conception to implementation and evaluation.
- Utilize diverse methods, including community meetings, surveys, focus groups, and online platforms, to ensure the participation of a wide range of community voices.
- Provide resources and support to enable meaningful participation, such as language interpretation services, childcare assistance, and transportation vouchers, to remove barriers to engagement for marginalized communities.

Prioritize safety by addressing the hotspots and implementing public awareness campaigns

- Identify locations with high rates of traffic crashes or incidents of crime, and implement targeted interventions to improve safety, such as traffic calming measures, improved lighting, and enhanced law enforcement presence.
- Develop public awareness campaigns to educate community members, particularly vulnerable road users such as pedestrians and cyclists, about safe transportation practices and the importance of adhering to traffic laws and regulations.

- Collaborate with local stakeholders, including community organizations, schools, and law enforcement agencies, to promote a culture of safety and encourage active participation in safety initiatives.

Ensure transportation affordability, especially for marginalized communities

- Provide subsidies or financial assistance programs for low-income individuals and families to offset the cost of transportation, such as discounted transit fares, subsidized ride-sharing services, or vouchers for transportation-related expenses.
- Advocate for policies that promote affordable housing and transportation options in tandem, recognizing the interdependence of housing and transportation affordability in achieving overall economic stability for marginalized communities.

Encourage the use of green transportation options to improve air quality

- Promote the adoption of green transportation options, such as public transit, walking, cycling, and electric vehicles.
- Invest in the expansion and enhancement of public transit infrastructure, including the development of bus rapid transit systems, light rail networks, and pedestrian and cycling infrastructure, which provides viable alternatives to car travel.
- Implement policies and incentives to encourage the use of electric vehicles, such as tax credits, rebates, and charging infrastructure incentives, to accelerate the transition to cleaner transportation technologies and reduce reliance on fossil fuels.

Policy Implications

Reallocating resources towards areas with historically less investment; and maintain transparency in funding allocation

- Conduct an equity assessment of current transportation funding allocations to identify disparities in investment between different communities.
- Improve transportation infrastructure and services in marginalized and underserved communities.
- Establish transparent funding allocation processes that involve community stakeholders in decision-making and ensure accountability and equity in resource distribution.

Data collection and monitoring, data disaggregation by race, income, and ability is crucial

- Enhance data collection efforts to gather comprehensive information that are disaggregated by race, income, ability, and other relevant demographic factors.
- Develop robust monitoring systems to track progress towards transportation equity goals and evaluate the effectiveness of interventions and policies.

Partnerships with health departments, environmental agencies, and community organizations

- Foster partnerships and collaboration with health departments, environmental agencies, and community organizations to address the intersectionality of transportation with health, environmental justice, and social equity.

- Engage community organizations and grassroots initiatives in transportation planning processes to ensure that interventions are community-led and responsive to local needs and priorities.

Regularly update engineering standards to reflect the latest best practices in safety and sustainability

- Review and update engineering standards and guidelines to incorporate the latest best practices in safety, accessibility, and sustainability.
- Ensure that engineering standards prioritize the safety and mobility needs of all road users, including pedestrians, cyclists, public transit users, and motorists.
- Incorporate principles of complete streets design, universal design, and Vision Zero initiatives into engineering standards to create transportation infrastructure that is safe, accessible, and inclusive for all users.

Ensure compliance with Environmental Justice (EJ) standards to prevent disproportionate negative impacts on marginalized communities

- Implement EJ assessments and analyses to identify potential disproportionate impacts of transportation projects and policies on marginalized communities.
- Develop strategies to mitigate adverse impacts and ensure that transportation projects comply with EJ standards and regulations.
- Engage with affected communities and stakeholders in the EJ process to ensure that their concerns and priorities are addressed in decision-making and project implementation.

CHAPTER 4: DEVELOPMENT OF EVALUATION METHOD

In this chapter, the team utilized the outcomes of the conducted literature review and interviews to develop an approach for evaluating transportation equity. The team also considered the concerns defined in earlier chapters and aimed to address them. In addition, the efforts in this chapter aim to address the lack of a comprehensive and flexible model to assess equity in transportation systems. In developing the model, the team focused on considering the granule component of transportation systems, given infrastructure systems.

Infrastructure systems are vital components and deliver services for sustaining human life. Infrastructural equity pertains to fairness in mobility and accessibility to meet the needs of all community members. The primary objective of infrastructural services is to provide equal socio-economic opportunities containing accessible and cost-effective choices, tailored to the needs of the demographic data such as population, particularly population groups that have received inadequate services. In recent years, equity was defined as a multi-disciplinary concept of politics, economics, and environmental science. In addition, the precise definition of equity variables can depend on the particular context. In this context, the Department of Transportation and Federal Highway Administration (FHWA) concentrated on the equity definition that provides the distribution of outcomes, rather than the broader concept also concerned with the participation of marginalized groups in policy processes (*111–115*).

Equity Metrics, Formulations, and Implications

Current studies have focused on accessibility, environmental impact, and safety. However, currently, there is no established standard for assessing equity, and there needs to be more examination of the equity metric. Clark et al. (*116*) outlined the process of developing an equity-focused resilience metric that evaluates the social consequences of infrastructure disruptions on households. In this formulation, the burden of a household to access a given infrastructure service point is defined as a function of a household's relative need for accessing a particular service type divided by that household's accessibility to that service. For a population group with similar household characteristics, the following equation for quantifying the social burden of infrastructure disruptions was offered as follows (*116*)

$$\beta_{\mathrm{P.S}} = \frac{N_{P.S}}{A_{P.S}} \quad (1)$$

Where $\beta_{\mathrm{P.S}}$ is the social burden for population group p to achieve capability types $s(hours)$, $A_{p.s}$ is the accessibility of population group p to capability type $s(hours^{-1})$, and $N_{p.s}$ is the relative need of population group p to achieve capability type $s(unitless)$. In additional studies, equity-focused social burden metrics based on the cost-effective impact were formulated and emphasized applying the social burden as an equity metric for infrastructure disruption (*117*, *118*). The highlights of the study were applying social burden as a resilience metric by quantifying it following a significant disruption to infrastructure, specifically, quantifying a metric for events in which infrastructure systems are a major component of the disruption. In this formulation, the burden of a household

to access a given infrastructure service point is defined, including opportunity cost, as follows (*118*):

$$\beta_{\mathrm{P.S}} = \frac{N_{P.S}}{A_{P.S}} = \frac{N_{P.S}}{\sum_h \sum_j f_h + b_j + C_{h.j}} \quad (2)$$

Where fh is the total travel costs for household h to achieve capability via service location $j(hours)$, bj is the total direct costs for household h to achieve capability via service location $j(hours)$, and $Ch.j$ is the opportunity cost (time and cost) for household h to achieve an important capability via service location j.

Jones and Armanios (*119*) presented a quantitative framework to assess the social equity impacts and incorporated social equity metrics into infrastructure analyses in terms of fairness in the potential flood damage. By conducting analyses on Pennsylvania's bridge system, it was revealed that the factors influencing the selection of bridge location have a significant impact on social equity than the structural modifications that occur after the bridge construction. Specific variables, such as demographics, income, transportation, education, and family-related factors, that are consistently correlated with structural change effects were considered. The probability of a tract being chosen for the building of a new restrictive bridge was examined to achieve the selection of the equity model (equation 3). This selection effect is of interest to recognize if there are associations between the decision to build a new bridge in a tract based on the population residing there before its construction process.

$$Logit(p(x)) = log \frac{p\,(x)}{1-p\,(x)} = \beta_0 + \gamma_k X_{k.i.t} + \delta_t + e_{i.t} \quad (3)$$

Where $Logit(p(x))$ is the probability that a variable designating a new restrictive bridge was built in the census period, in tract i of the census year t, γ_k = vector of control variable coefficients; X is the vector of variables of social interest and is fixed effect for each census year (*119*). As suggested by the U.S. Department of Transportation, equity can be involved in assessing the infrastructure characteristics or conditions in neighborhoods with high concentrations of socially vulnerable populations (such as low-income households, minorities, and households without cars) compared to those in adjacent neighborhoods or regional averages. Li et al. (*120*) explored infrastructural equity by considering the distribution of infrastructure characteristics in correlation with socially vulnerable populations. By comparing different areas to adjacent neighborhoods and regional averages, the spatial patterns of infrastructure disparities were assessed.

By assessing infrastructural equity with statistical models harnessing socio-economic measures and normalizing it into income to estimate the relative risk, an equity metric was proposed using vulnerability analysis and limit state functions using principal component analysis (PCA) as follows (*120*)

$$\mu = \frac{M_{STD}}{M} \quad (4)$$

Where M_{STD} represents substandard measurable infrastructure components within the neighborhood and M is the total number of measurable components within the neighborhood.

Several studies contributed to assessing infrastructural equity by the application of optimization procedures. Seyedashraf et al. (*121*) addressed social equity in urban planning and proposed a framework that integrates spatial analysis, and decision-making tools to identify possible inequities in the distribution of sustainable infrastructures. By integrating spatial equity principles into the design process spatial equity in damage distribution was formulated, and a multi-criteria design framework to address spatial equity was proposed. The result of their study suggested that using traditional optimization models can be effective in having an unequal distribution of urban infrastructure services. In addition, an equal distribution of flood damage among urban neighborhoods was not guaranteed by achieving an equal spatial distribution of assets. In another study, Dai et al. (*122*) introduced a stochastic optimization approach, which was noted as a measurement of income inequality. In their research, managing water distribution in a way that balances both equity and efficiency considering the social and economic implications was investigated. A coefficient based on chaotic optimization was introduced to evaluate the equality of water infrastructures among water users, and multiple objectives were used to reflect the tradeoff between equity and the benefit of water allocation schemes. By incorporating social, economic, and environmental factors, Xu et al. (*123*) presented an intergenerational equity-based optimization model for the ide decision-making processes of water infrastructures. Both intra- and intergenerational equities were integrated to meet adequate water resources for future generations. Additionally, to effectively balance social development and water management, the mean economic benefit and efficiency within a multi-objective model were coordinated.

Equity metrics can also measure other infrastructural aspects such as temporal equity, income equity, racial equity, labor equity, bike equity, and environmental equity. However, there is no available equation or comprehensive formula for the equity assessment. Mayfield et al. (*124*) examined environmental equity burdens and benefits through quantitative analysis across different communities, and the need for policy interventions to address the social equity concerns associated with the infrastructures was highlighted. Fell et al. (*125*) proposed a framework to analyze the distributional impacts of low-carbon transitions, considering income, employment, and social welfare factors. According to their research, there are limitations in current equity measurements, and there is a need for ensuring equitable outcomes and minimizing negative consequences for vulnerable populations. Batel et al. (*126*) noted the significance of considering social factors in the equity of infrastructures. Social acceptance, including the influence of values on public attitudes toward environmental aspects, was discussed. The importance of a multidisciplinary metric that integrates social, economic, and environmental aspects was emphasized in this study to promote sustainable and equal transitions. Lehmann et al. (*127*) focused on the spatial implementation of infrastructural projects considering environmental, social, and economic aspects. James et al. (*128*)

investigated the potential benefit of diversifying an equity portfolio by investing within equity sectors and analyzing the impact of financial aspects such as income on the equity of the structures. Joshi et al. (*129*) proposed an equity index called project equity which analyzes the distribution of infrastructural projects throughout the transportation network.

Equity Analysis and Measurements

Upon reviewing the current metrics in the above section, it was observed that most of the existing approaches for equity analysis can be categorized into three steps which are population, cost/benefit, and inequality measurements respectively **Figure 7**.

Population measurement can be defined as selecting population segments from demographic data and it can be contrasted in terms of cost and benefit. Depending on whether horizontal equity (based on geographic location) or vertical equity (based on socioeconomic position, race/ethnicity, or mobility needs), outcomes can be taken into consideration for either individuals or groups within the community. Although measuring outcomes can be impractical due to the scattered population and complex paradigm of human travel behavior within a multimodal transportation system, the development of activity-based travel demand models enabled such studies (*130*). Several population measurement strategies were used to evaluate equity. Outcomes among population groups were analyzed, using aggregated population data for spatial unit areas, such as census tracts, census blocks, or Traffic Analysis Zones (TAZs) obtained from the Census Bureau. The distribution of population groups can be contrasted by vertical equity and identified by spatial units and demographic characteristics including socioeconomic status. Race and ethnicity, education level, and age were considered the most common group classification in equity analyses (*131*, *132*). The percentage of each group residing within each spatial unit was used to determine each of the above-mentioned groups for analyzing equity (*133*).

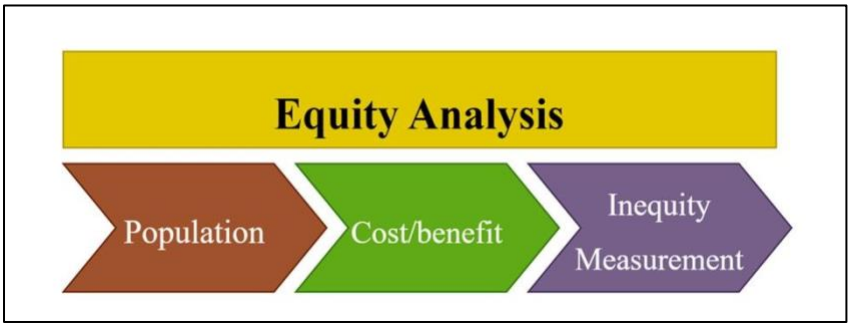


Figure 7 Characteristics of the existing equity analysis

The impact of the transportation networks on the target population groups can be quantified by cost and benefit measurement. Accessibility, traffic emissions, and safety were noted as significant factors for the measurement of the cost in equity analyses. For measuring cost-related accessibility that has been used in equity analysis, Currie (*134*) quantified the accessibility of the population zones as the ratio of the service area for the given facility zone. The proposed approach accounted for spatial coverage to measure the degree of access within the service level of the

system. Subsequently, coverage-based measures were applied to investigate horizontal and vertical equity (*135*). The reachability-based metrics were suggested by some researchers to estimate the capability of population zones and to count how many population zones can reach with the given budget such as cumulative accessibility function (*136*, *137*). In the equity literature, exposure to traffic emissions can frequently be determined by calculating the distribution of traffic-related air pollution (or surrogates) in the region and estimating exposures by correlating human locations in space and/or time with pollution levels (*138*). The concern of traffic safety in equity studies has been based on examining the injuries and fatalities and crash rate. Extensive investigations have been conducted to explore effective factors such as the number of traffic injuries or casualties, the socio-demographic characteristics, the level of physical development such as density of employment, and environmental elements such as road density and traffic volume in a particular region (*139*).

Furthermore, three main approaches were suggested to assess the equity of the performance of infrastructure systems as shown in **Figure 8**. The first method for evaluating the equity performance of a transportation system is to conduct a mismatch analysis using descriptive statistics of cost/benefit measures This approach entails presenting the distributions of cost/benefit measures through maps or tables and comparing them manually to reach the performance pattern of equity for each population zone (*140*). Mismatch analysis can be counted as an intuitive method, however, there is a lack of quantitative information in the result of assessing equity performance by this method. Therefore, quantitative analysis methods utilizing statistical, or inequality index formulations have been suggested.

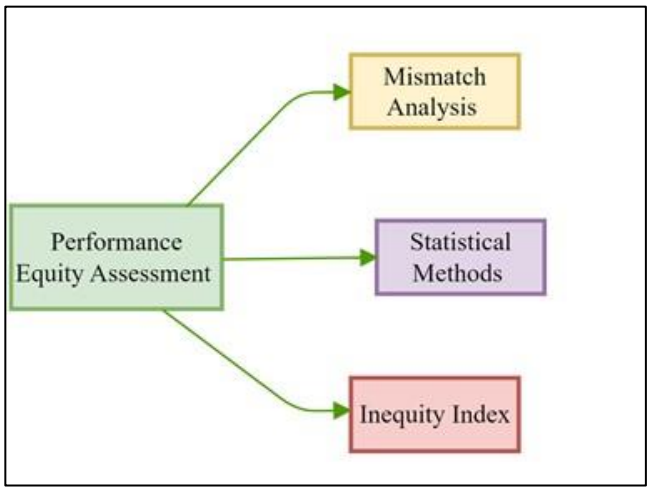


Figure 8 Equity assessment categorization

The subsequent procedure is statistical measures that are commonly applied to quantify inequality in an attempt to assess horizontal and vertical equity. Univariate metrics that analyze the distribution of a cost/benefit measure among geographic units (such as census block groups) can be used to investigate horizontal inequity. These measurements include the distribution's

variance or standard deviation (*141*), the inter-decile range (*142*), and the ratio of the highest to lowest values. Alongside the univariant measures, analysis of variance (ANOVA), correlation analysis, and regression modeling are notably utilized in studies to assess vertical equity (*133*, *141*). It should be noted that the level of inequality between cases cannot be compared by statistical approaches, and to address this limitation there is a need for the inequality indices.

Inequity measurement

It is imperative to recognize that the framework of equity cannot be conflated with equality, and they are not inherently similar concepts. The notion of substantive equality aligns with the formulation of equity. In literature, equality emphasized the significance of individuals should encounter an equitable distribution of resources and homogenous impacts (*142*). Nevertheless, inequity is a subset of inequality considered unfair by social norms such as health disparities arising from exposure to hazardous gas emissions (*143*, *144*). Inequality indices have been extensively applied in economics, social science, and public health to provide a measure of the inequality degree with different variables, including income across the distribution of the population. The Gini index, Atkinson index, and Theil's entropy index are recognized as inequality indicators. To evaluate the distribution of wealth or income among demographic data Gini index has significantly been used in equity performance studies, and it has a range of 0 to 1, where 0 represents perfect equality and 1 represents perfect inequality (*145*). Although the Gini index can be adapted for evaluating horizontal and vertical equity of targeted population groups, it cannot be decomposed into additive attributions from subgroups, and this drawback can be detrimental to vertical equity analysis (*144*).

The Atkinson index emerged as a measure to quantify income inequality (*146*) and was developed as an indicator for inequality evaluation in health benefit analysis (*144*). It ranges between 0 and 1, with 0 indicating complete equality and 1 indicating complete inequality. In addition to adopting concepts of inequality indicators from economics, researchers have evolved inequality indicators for population groups. Harner et al. (*147*) proposed a risk index to determine whether socio-demographically disadvantaged groups are more likely to be exposed to environmental hazards than the rest of the population. A subgroup inequality index was formulated by Stuart et al. (*141*) that measures the extent to which a particular subgroup experiences disproportionate exposure to both the costs (e.g., pollutant emission sources) and benefits (e.g., regulatory monitoring) of an environmental management system.

Gaining a deeper understanding of past endeavors can provide a solid basis for developing a suitable methodology to evaluate equity in emerging infrastructure systems. However, despite the vast array of equity metrics and parameters, there remains a pressing need for a single, all-encompassing equation that facilitates the evaluation of equity and inequity. Through a review of previous remarkable studies, it is evident that equity metrics have transformative potential to develop and evaluate various aspects of infrastructural equity, and the necessity for such an approach is deduced from the observed gaps. By embracing sophisticated methodologies and

employing probabilistic modeling, we can propose a probabilistic-based equity of unprecedented precision, thereby driving the infrastructural equity metric and safety to new frontiers. The running paper introduces an innovative methodology and framework that push the boundaries of existing practices to overcome the remaining limitations in equity indices based on the comprehensive review. These advancements aim to achieve rigorous equity and inequity metric for the infrastructural assets and propose Agent-based equity modeling for considered elements.

Model Development

This study proposes a novel methodology to address the limitations of existing equity indices and enhance the reliability of existing evaluations. The development of this methodology stems from recognizing the need for improved procedures that can provide reliable equity assessments and measurement of its metrics. By introducing innovative solutions, including Agent-Based Equity Modeling (ABEM), and Probabilistic Based Equity Model (PBEM), this methodology aims to transform the field of infrastructural equity evaluation. Through these advancements, this methodology attempts to provide researchers, agents, and stakeholders with a robust framework for quantifying accurate equity elements and equalizing variables. The prelude establishes the overview for the forthcoming chapters, which will thoroughly examine the essential steps of the methodology and provide development their potential applications and the improvement they bring to the respective field.

Agent-Based Equity Modeling

The notion of equity has been increasingly considered a notable research element, leading to its growing inclusion in transportation discourses. This normative consideration has been driven, in part, by rising levels of inequality and increasing environmental risks (*148*, *149*). Given its involvement in these discourses, agent-based modeling (ABM) practitioners must contemplate the tool's capacity to impede equity. Agent-based models have since been applied in several publications in a broad range of academic disciplines (*150 – 152*). ABM can be built for a diverse range of purposes, ranging across levels of prediction and explanation (*153*). Correspondingly, a range of levels of complicatedness and empirical embeddedness can be taken from the agent-based models (*154*).

Agent-based modeling (ABM) can be defined to present an opportunity to address equity concerns. By simulating interacting and heterogeneous populations, agent-based models enable the study of how system-level and distributional outcomes emerge through top-down and bottom-up processes. This modeling approach is appropriate for covering issues of (in)equity, in contrast to approaches that assume homogeneity among the population groups. Notably, these distinctive features can be served as inspiration for pivotal advancements in the ABM field, such as Schelling's segregation model, which sought to explain the emergence of macro-level inequalities from micro-level processes (*155*). Equity elements in ABM modeling development can be categorized into social context, abstraction, and interpretation. In the social context, agent-based models had been influenced by social practice and power relations (*156*). In this process, a position of influence can

be assumed by decision-making such as data selection, model design, and result interpretation. Abstraction has served two purposes: to make model development feasible and to enable the representation of intricate concepts in computer code. The modeler has been responsible for making decisions regarding which aspects of the target system should be excluded, reconciling diverse perspectives, and establishing connections between observable characteristics (*157*, *158*). The complement to abstraction is the interpretation which can highlight that meaning should be attached to model outputs (*159*).

In the context of the infrastructural (in)equity, agency role, infrastructure (asset) performance, and target group characteristic are important factors to incorporate into a model. Hence, an ABEM framework is proposed herein by modeling the target group of study as a user, agency, and asset behavior. Each agent is considered separately and possesses an inherent dynamic, as well as closed-loop links that allow it to have interactions with other agents. To be more specific, a group agent as a user might impose varying demand levels on an asset agent, while the asset provides services associated with the capacity of the user. In this study, a new platform for Agent-Based-Equity-Modeling (ABEM) methodology is proposed that entangled ABM in the context of infrastructural equity is tabulated in **Table 2** and the result of a closed loop modeling is depicted in **Figure 9**.

Table 2 ABEM Modeling Features

# Phase	ABEM Task Description
1	Assessing equity elements, exploring the distribution of socio-economic factors, or examining the impacts on marginalized populations based on location.
2	Identifying the key variables that contribute to equity, such as income, demographics, location, health, and demand of the systems.
3	Proposing assets and their attributes of built environment and sustainability.
4	Defining the agents of such as service providers and the Department of Transportation (DOT).
5	Determining the attributes of agents, including the performance levels and interactions.
6	Indicating the decision-making processes and specifying agents' interactions.

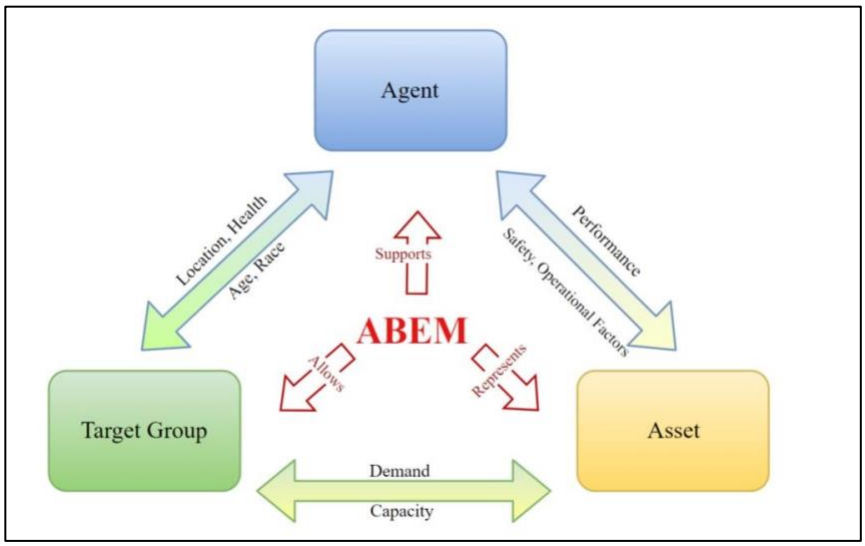


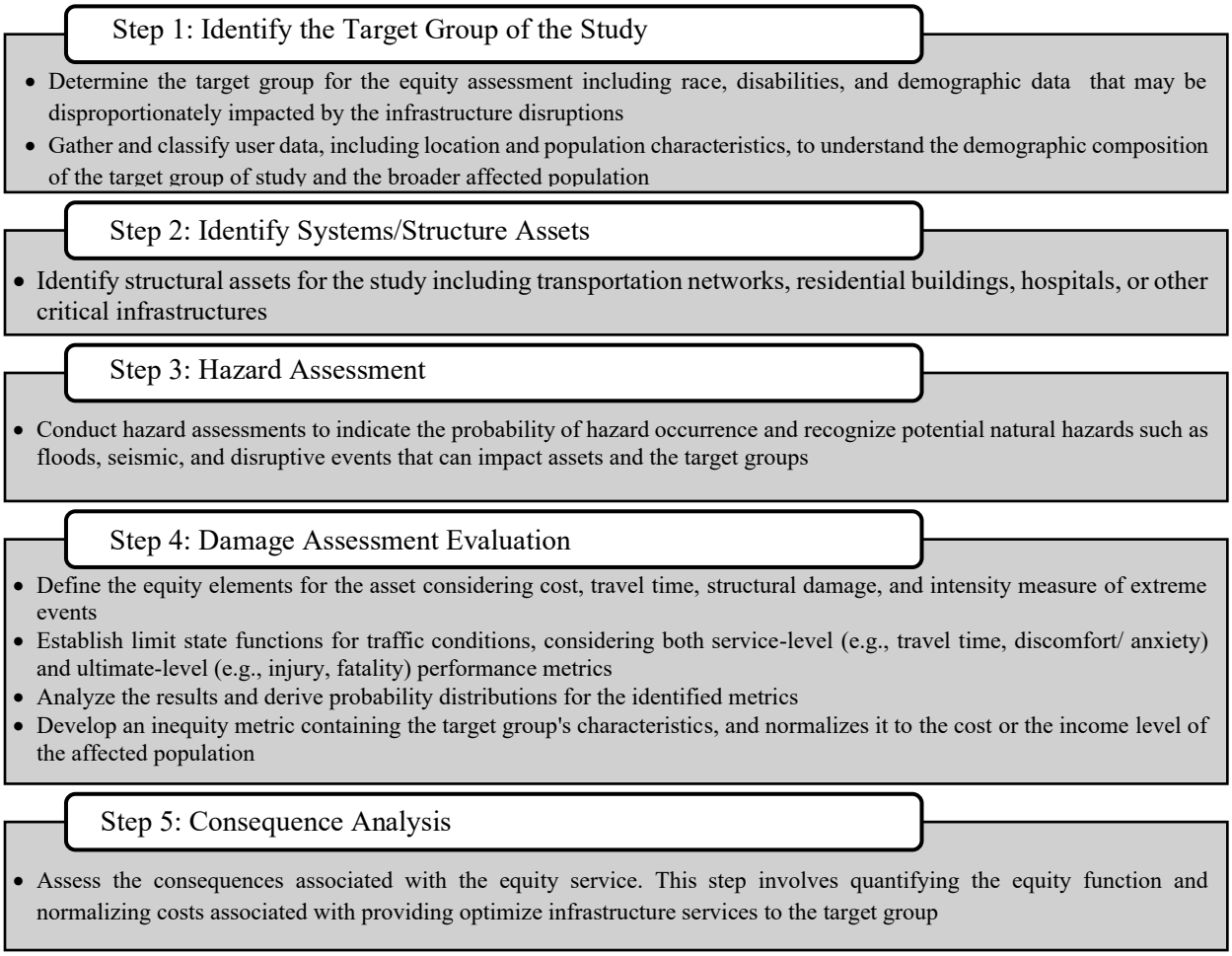
Figure 9 Agent-based equity model

Probabilistic-Based Equity Models

This section introduces a comprehensive procedure for assessing equity/inequity metrics, using a probabilistic-based approach to indicate uncertainties, identify main parameters, and facilitate evaluations. Probabilistic modeling can be defined as a statistical technique that leverages the impact of random events or actions to predict the likelihood of posterior events. This quantitative modeling approach can project multiple potential results, some of which may extend beyond recent historical occurrences. Probabilistic models have been extensively utilized in reliability, resiliency, and risk metrics of infrastructure studies. These descriptive metrics provide paths to evaluate the preparedness for various failure modes such as the impact of extreme events and infrastructure fatigue (*160*, *161*). Quantitative probabilistic-based resilience measurements have been introduced in analytical and numerical approaches to support better decision-making for transportation infrastructure (*162 – 164*). Bocchini et al. utilized the resilience index (*165*) based on the functionality recovery curve after an extreme event. They suggested a complementary probabilistic-based approach rooted in the well-established risk assessment framework. According to their study, the impact of the infrastructure and its service states on society in operational conditions and after exceptional events should be weighted by the associated probabilities of occurrence and combined in a global impact assessment (*166*). The probabilistic model checking approach for transportation risk assessment, and contingency evaluation was elaborated for modeling risk-prone transportation tasks and facilities (*167*, *168*). Apart from this, reliability analysis (*169*) can be counted as a potent probabilistic tool to evaluate transportation network vulnerability, where the failure of part of the transport infrastructure would have the most severe effects on access to specific locations and over-system performance (*170*).

According to existing applications, probabilistic models are practical techniques to capture uncertainty, estimate the robustness of the equity assessment, and evaluate equity metrics in infrastructural systems. In a broader context, the proposed Probabilistic-Based Equity Model

(PBEM) shows the effectiveness of applying integrated probabilistic techniques to assess the damage to transportation networks and identity all key equity parameters enabling improvements in the design performance of existing and future infrastructures. Subsequently, the motivation of the proposed method is to offer a structured approach for evaluating equity/inequity, considering the unique attributes of the target group, the likelihood of hazards, damage assessments, and the implications of equitable services. Doing so empowers decision-makers to make well-informed choices and fosters fairness in infrastructure development endeavors. This proposed framework is broken down into five main steps, which are presented below.



Limit State Functions

The limit state function is a mathematical expression to establish the threshold between acceptable and unacceptable performance of the considered infrastructure component (*169*, *171*). The equity limit state functions can be defined as the limit of the input variables of the level of discomfort and failure scenarios. This function accurately estimates the probability level for infrastructure assets that experience multiple failure modes and exceed the comfort level, including those caused by extreme events. The new set of limit state functions can be proposed for ultimate, service, and extreme events. The ultimate limit represents infrastructure or human encounters with physical damage or a high fatality rate. The limit state function for ultimate events can be used to determine the point at which the infrastructure capacity exceeds the acceptable limit. Serviceability encompasses daily loads without causing discomfort, considering cost and waiting time. It should be noted that a limit state function can be defined for extreme events such as earthquakes and floods. The proposed equity limit state functions for the ultimate (g_U) and service (g_S) are presented as follows:

$$g_U = R_F - Q \quad (5)$$

$$g_S = R_C - Q \quad (6)$$

Where R_F represents fatality rate distribution, R_C indicates the cost distribution associated with waiting time, and Q represents loading scenarios such as traffic flow.

(In)Equity Function

As mentioned in the previous sections, the current equity indices have certain limitations. The existence of broad and difficult-to-identify equity parameters reduces the likelihood of achieving a comprehensive equation that encompasses all aspects. As a solution to address these barriers, implementing conditional equity functions can address can incorporate and consider more adaptable factors. Moreover, by comparing different scenarios, decision-makers can gain valuable insights to promote balance, and by introducing equalizer variables, equity across diverse dimensions can be achieved. Consequently, by normalizing the costs associated with critical factors (e.g., income, time) the equity function converts to a more consistent assessment of (in)equity across varying inputs. By incorporating the proposed solutions, equity indices based on the cost and time for the prior and posterior hazard of extreme events are proposed respectively in Equation 7 and Equation 8.

$$E_{Location|\,\text{Age.Race.Health}} = C\,(F.I.V) \quad (7)$$

$$E_{Location|\,\text{Age.Race.Health}} = P_H\,C\,(F.I.V) \quad (8)$$

Where C indicates the cost of injury, cost of fatality, and cost of vulnerability, and PH represents the probability of hazards. Accordingly, a new full probabilistic inequity function (IE) was proposed to evaluate the cost associated with the damage condition of the infrastructural

components concerning the given engineering demand parameters. This probabilistic index takes the impact of the cost and failures as a result of extreme events. The inequity function for the cost of asset damage and the extreme event such as seismic is presented in Equation 9.

$$IE: \iint F\ (Cost|D_H)\ f(D_H|IM)\ f(IM)dIM\ dD_H \quad (9)$$

Where D_H = the asset damage, IM = the considered intensity measure. F(.)= CDF of the cost by the given condition of the damage, f(.) = is the PDF of the intensity measure. The proposed equation defines how the costs and impacts of damage vary with the magnitude or intensity of the extreme event and it shows the relationship between the severity of an extreme event and the entailed consequences in terms of damage and costs. In other words, this probabilistic function provides a way to evaluate the risk associated with such extreme events and incorporate the probability of occurrence. This index is a valuable tool for decision-makers to better understand the overall risk and have more informed choices in risk mitigation strategies.

Summary

This chapter provides a review and presents a new equity-based limit state function for estimating the performance of the systems. In the proposed equity investigation, an advanced damage assessment evaluation was then applied to establish limit state functions of equity elements. Through the utilization of equity elements and leveraging conditional probability, a new function to measure inequity was formulated, which was normalized to income and costs, yielding inequitable indices. By employing the inequity measurement, it becomes possible to measure equity from its inverse function. This assessment allows for a deeper understanding of disparities, providing valuable insights into the extent of inequality and the areas where corrective measures are needed to promote equitable outcomes. In addition, as a result of reviewing existing literature on equity assessment of transportation systems, the performance measures utilized for this evaluation have been methodically updated and categorized for infrastructure systems and visually depicted in **Figure 10**. This representation can be served as a comprehensive overview of the diverse indicators employed to gauge equity in infrastructural systems.

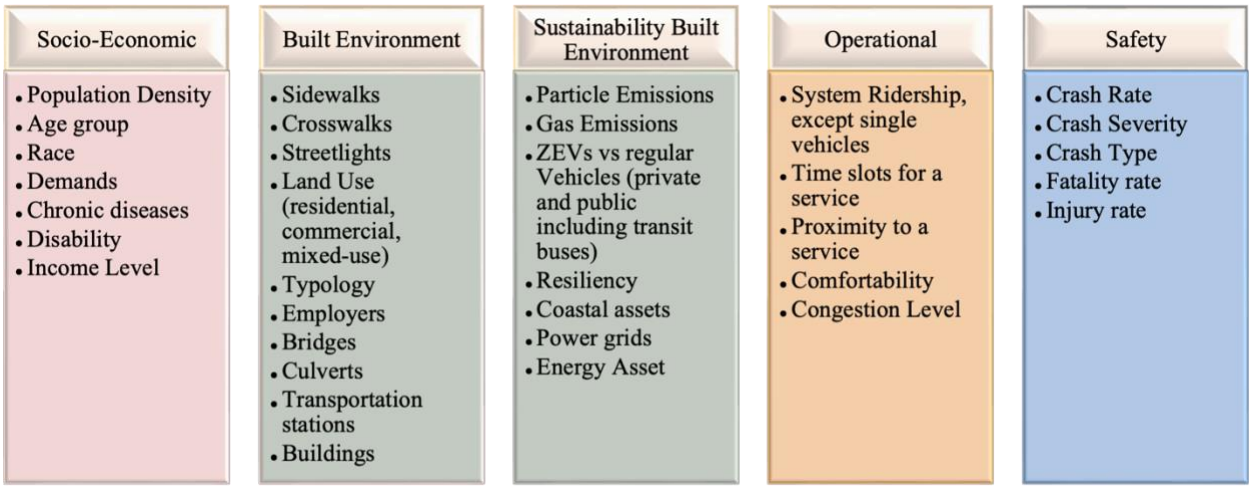


Figure 10 Performance measures of infrastructural equity

By proposing agent-based equity modeling (ABEM), equity dimensions were illustrated. In addition, by unifying existing indices and proposing a novel probabilistic-based equity metric, significant steps have been taken toward addressing limits and enhancing fairness in infrastructure development. The proposed approach tackled the disparities in the current literature, providing a more robust method for evaluating equity for various agents involved, including communities, hazards, assets, and agencies.

The proposed probabilistic-based equity function has the potential to notably improve infrastructure development. Policymakers can ensure that the cost and benefits of infrastructural development are dispersed more equally across society by taking equity issues into account. This may result in the development of more sustainable and inclusive societies where everyone has equal access to resources and opportunities. In addition, implementing such equity-focused approaches in infrastructure planning can contribute to improving decision-making. For the following studies, future research can focus on refining the proposed metrics, validating with extensive data sets, and further exploring potential implications for enhancing infrastructural equity.

CHAPTER 5: CONCLUSION

The exploration of equity in transportation systems through this report has revealed the intricate and multifaceted nature of the concept. The literature review provided a comprehensive examination of equity, highlighting its broad scope beyond mere access to mobility services. It illuminated the interconnectedness of equity with socioeconomic disparities, environmental sustainability, public health, traffic safety, and social cohesion. In addition, it highlighted the directions of discussing and unpacking equity in transportation systems in the current literature. The predominant aspects of transportation equity discussions were highlighted, these included: defining equity in transportation systems, the barriers to maintain equity, challenges associated with transportation inequity, approached to enhance current status, future directions. This holistic understanding fed conducting the interviews with professionals and developing the transportation equity assessment model.

In the third chapter the team sought practical understanding of transportation equity by interviewing professional who had experience in maintain transportation equity. This approach complemented the theoretical understanding from the literature review an enhanced the development of the evaluation model. Moreover, the chapter concluded with recommendations and policy implication defined based on the discussions with the interviewees. In addition to the importance of this chapter in comprehending the practical insight of transportation equity, it provided an enriched source for policy makers and transpiration planners to learn from pervious experiences. The chapter highlighted that transportation equity is affected by several factors and which work as determinants to define performance indicators to evaluate transportation equity.

Furthermore, the development of an equity-based limit state function and the proposed agent-based equity modeling (ABEM) in the fourth chapter presented innovative approaches to evaluating infrastructural equity. These methodologies offer valuable insights into the extent of inequality within transportation systems and provide a framework for identifying areas requiring corrective measures to promote equitable outcomes. By leveraging advanced damage assessment evaluation and probabilistic-based equity metrics, policymakers and planners can make more informed decisions to ensure that infrastructure development benefits are dispersed equitably across society.

The integration of equity considerations into transportation planning and infrastructure development is crucial for promoting social justice, enhancing accessibility, and improving overall quality of life for all individuals, particularly vulnerable and marginalized populations. As cities grapple with urbanization, technological advancements, and the imperative to combat climate change, prioritizing equity as a fundamental pillar in shaping transportation systems is paramount. Moving forward, future research should focus on refining the proposed equity metrics, validating them with extensive datasets, and exploring potential implications for enhancing infrastructural equity. Collaborative efforts among experts, communities, and governments will be essential in addressing existing disparities and advancing toward more sustainable, efficient, and equitable transportation networks.

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