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Incorporating Social equity in Infrastructure Performance Evaluation

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ABSTRACT: Public infrastructures are complex systems that act as the backbone for cities' livability and economy. Recent directions from different levels of government encourage the development of infrastructure asset management plans to track infrastructure performance and plan for renewal and forecast activities. Even though infrastructure performance metrics have been widely explored, the studied impacts are often related to the overall community without granular investigation across different social metrics. Areas of more social vulnerability (e.g., lower median income) are typically more impacted by infrastructure service degradations. In this paper, a framework for developing equity-based levels of service has been proposed based on available data on community demographics and their granularity. The proposed approach can be applied to all types of infrastructure assets and has been demonstrated in this paper using an example of a publicly available municipal asset management plan. Developing and tracking levels of service with respect to different equity metrics provides decision-makers with the information required for evidence-based decisions that reduce inequities within the community.

1. INTRODUCTION

Civil Infrastructure refers to the physical structures and facilities needed for the operation of a society, including roads, buildings, and water/sewer networks. To maintain service quality, municipalities and other large asset owners develop maintenance and rehabilitation (M&R) projects that aim to preserve and enhance the assets' levels of service. Another type of projects that can be undertaken by asset owners is growth projects where new facilities are developed to increase the accessibility and performance of the entire portfolio. These projects, however, typically exceed the available funding, which forces the asset owners to decide whether a project can go ahead or get deferred. Project prioritization is a decision analysis where project proposals are analyzed based on their expected benefits, according to a set of evaluation criteria (Krapp et al. 2021). Among these criteria are the condition of the asset as well as its intended performance, often referred to as Level of Service (LOS). While portfolio-wide prioritization procedures are common, they overlook the gaps in performance among the individual assets, particularly on the social equity front.

Similar to the performance of an asset portfolio, a large community (e.g., a city) often shows disparities in the demographic and socio-economic attributes of its building blocks (e.g., neighborhoods). Such disparities cause increased segregation in poor areas and anxiety in wealthier areas (Nikoofam and Hoskara 2022). These inequalities not only directly affect living conditions, but can lead to social conflicts such as crimes and riots (Shao et al. 2022). To alleviate these issues, social equity aims to achieve a fair and appropriate resource distribution between groups (Li and Fan 2020; Litman 2022). In July 2020, the ASCE revised its code of ethics to state that "engineers shall consider the diversity of the community and shall endeavor in good faith to include diverse perspectives, in the planning and performance of their professional services." (ASCE 2020). As such, integrating social equity in measuring engineering performance aims to reduce gaps in the performance of assets serving advantaged vs. disadvantaged groups in a society (Behbahani et al. 2019). While advances in geographic information technology have made analyzing spatial allocation of assets and services easier (Li and Fan 2020), a comprehensive strategy for developing Equity-led LOS is still lacking (Nikoofam and Hoskara 2022). Existing research has focused on the adverse impacts of infrastructure inequality on the population's health, productivity, and education level (Shao et al. 2022). However, how to measure and adapt the infrastructure performance to reduce such adverse impacts has received relatively little attention (Nikoofam and Hoskara 2022). Hence, this paper aims to present a generalized methodology, applicable to different asset types, to consolidate social equity into infrastructure performance evaluation and levels of service.

2. LITERATURE REVIEW

M&R of any infrastructure is commonly prioritized using cost-benefit approaches (Menendez et al. 2013). While the “cost” typically refers to the estimated cost of the M&R project, the “benefit” can take on multiple shapes and forms. Examples of a gained benefit would be the improved condition of the asset, the reduced risk of failure, or the improved service to the community (where the number of people using the assets is taken into consideration). What is common in these definitions is their aim towards the “greater good” where the overall portfolio condition and performance are prioritized. Unfortunately, existing approaches often overlook, if not intentionally aggravate, performance gaps across communities with different demographics. Underserved communities are typically less equipped to draw attention to their deteriorating assets (Mohai and Saha 2007; Kontokosta et al. 2017). So, a system that looks into the number of complaints as a metric will be biased towards the wealthier neighborhoods that are more likely to complain about their infrastructure. Disadvantaged groups thus become more inherently sensitive to disruptions to their infrastructure performance (Mohai et al., 2009; Houston et al., 2014; Rowangould, 2013; Durrant, 2017; Collins et al., 2020). Hence, recent studies have emphasized the need to actively consider social equity in infrastructure performance assessments (Du et al. 2020; Kothari et al. 2022; Manaugh et al. 2015).

Analyzing infrastructure performance using an equity lens is a relatively recent topic, particularly after 2020 (Seyedrezaei et al. 2023). Some studies created the inequity metrics solely based on the infrastructure performance. For example, Okushima and Castano-Rosa (2020) analyzed access to energy sources in Japan and highlighted geographic locations that are “energy poor” although not socio-economically studied. Li and Fan (2021) studied the performance of the public transit network in the city of Charlotte, highlighting reduced service coverage as the distance from downtown increases. Similarly, Aman and Smith-Collins (2022) identified “transit deserts”, areas with high transit-dependent populations but insufficient transit service, within the city of Dallas, yet without considering the population’s socio-economic attributes. Kothari et al. (2023) analyzed the road network of two different cities and identified inequities within the road network based on its condition. However, instead of utilizing demographic data, their definition of a “disadvantaged group” is a group whose road condition is in the bottom 20th percentile. Other studies highlighted the impact of inequitable infrastructure. For example, Hackett et al. (2015) highlighted a correlation between access to healthy food options and physical spaces and childhood obesity. Mitra et al. (2021) analyzed mobility patterns within the elderly population, highlighting that elders from low-income families suffer the most after cessation of driving. Tizando-Aitken et al. (2021) have shown how public transport inadequacies can impede some communities’ access to quality education in Santiago, Chile.

Only few studies established the link between social attributes and infrastructure attributes and they are mostly focused on the water infrastructure, and this remains a research gap. Schnaider et al. (2019) correlated nitrate concentration in drinking water and the communities’ ethnic backgrounds. Wakhungu et al. (2021) studied different forms of equity in the city of Tampa, Florida, and compared them to the performance of the drinking water network. Mohanavelu et al. (2024) developed a prioritization framework for water infrastructure repairs that incorporates social equity considerations. The same gap is also prevalent at the municipal level. For example, the City of Ottawa’s Transportation Master Plan (City of Ottawa 2024) identifies equity-deserving neighborhoods based on their sociodemographic attributes and advises that these neighborhoods would be under “further consideration”, but no link to infrastructure condition or growth projects have been established.

Accordingly, this paper aims to provide a generalized framework that links infrastructure performance and the community's socio-economic considerations. The framework answers questions: (1) what data to collect; (2) How to analyze the data with respect to the established levels of service; and (3)How to present the analysis to guide M&R decisions?. These three questions are answered in the following sections of this paper, respectively.

3. PROPOSED APPROACH

As an important step towards efficiently incorporating equity into infrastructure decision-making, this paper aims to provide a generalized framework that links infrastructure performance and the community's socio-economic considerations. The framework answers three important questions: (1) what data to collect; (2) How to analyze the data with respect to the established levels of service; and (3) How to present the analysis to guide M&R decisions? These three questions are addressed in the three components of Fig. 1. These phases are necessary to integrate social equity into infrastructure planning and performance measurement. The first phase aims to align the demographic data (community) with the technical performance data (infrastructure). The second phase analyzes the infrastructure performance variations across the different communities, while the third phase presents the infrastructure assessment results in a form that supports equitable rehabilitation decisions. In each phase, "gatekeeping" questions are presented to scrutinize the data and help guide which performance metrics to focus on.

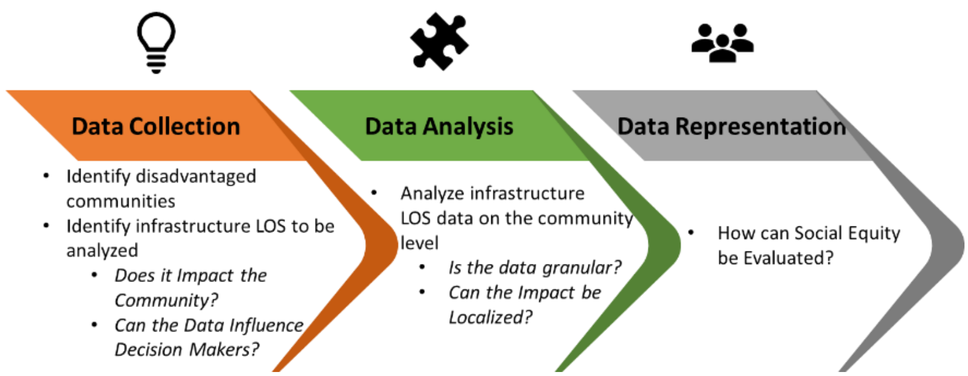

Fig. 1: Proposed Framework for Incorporating Social Equity Data into Infrastructure Assessment

4. EQUITY RELATED DATA COLLECTION

To assess the differences in asset performance between groups of different equity concerns, two main datasets need to align: the asset performance dataset, and the community socioeconomic dataset.
The collected socioeconomic data should help identify the groups with high equity concerns within the target population (e.g., equity-deserving neighborhoods within a city). Composite socioeconomic metrics (a score based on aggregating different criteria such as income, health, access to services, etc.) are now relatively abundant. For example, Osman and Faust (2021) proposed using the Social Vulnerability Index (SVI) developed by the Centers for Disease Control and Prevention. This index consists of different socioeconomic (e.g., employment, income), household (age, disabilities), and racial variables (CDC 2022). Different cities now have created similar equity metrics. Other examples include Tacoma, Washington (City of Tacoma 2024), Calgary, Alberta (City of Calgary 2022), and Ottawa, Ontario (Neighborhood Equity Index 2024).

These composite indices display a more comprehensive view of the target population. However, the methodology by which the metrics are created (e.g., the weighting and normalization of the different factors) can be scrutinized. Furthermore, relying on these indices blindly can lead to double counting if the index already includes the infrastructure metric that needs to be studied separately. The City of Ottawa's Transportation Master Plan (City of Ottawa 2024a) has adopted an approach that combines "the best of both worlds", breaking down Ottawa's Neighborhood Equity Index (2024) before recalculating a new "index" after removing all physical infrastructure related attributes to avoid double counting.

In the absence of such advanced metrics, extracting raw census data and developing one's own equity criterion can prove to be quite effective. Census databases which hold the house's or neighborhood's attributes can be geographically mapped to their location, making it possible to develop such spatial analyses easily (Omer 2006). For example, Mueller and Gasteyer (2023) used data from the US Census Bureau, using the average household income as the metric based on which an area's equity concerns are defined.

The infrastructure performance data would showcase the metric(s) that will be measured across the population under study. Such performance metrics are typically referred to as levels of service (LOS) which reflect the goals of the community (Federation of Canadian Municipalities 2003; ISO 2024). For a road network, the LOS could relate to the quality of the road expressed in the form of pavement quality index (PQI). For a water network, the LOS could relate to the reliability of the water supply expressed in the form of the number of pipe breaks. While the levels of service are numerous, there are two key questions that need to be answered "yes" for an LOS to be a good candidate for an equity-based study. (1) does the LOS have a direct impact on the community? And (2) will the results of tracking this metric across the smaller communities influence the decision-making process for future growth or M&R projects?

4.1 Does the LOS impact the community?

While municipal infrastructure intends to serve the community, not all infrastructure assets provide this service directly. Thus, tying that particular LOS directly to the community becomes challenging. Looking at facilities, examples of infrastructure that provide direct impact to the community include libraries or community centers since they are utilized directly by the community members. Examples of infrastructure that do not provide such "direct impact" or "first-hand experience" are governmental buildings and offices. Therefore, while the City of Ottawa has developed a specific asset management plan related to government services facilities (City of Ottawa 2024b), the LOS "percent of assets in fair or better condition" would not be eligible for an equity-based analysis. This is because although it is important to maintain healthy working conditions for staff, this does not have a direct impact on the end user of the service compared to other public-facing facilities such as libraries or fire stations.

Such "direct impact" can be measured in multiple ways. In the case of facilities, access to the services the facility offers can be measured through the average distance from the community to said facility (e.g., distance to the closest library). In the case of linear infrastructure, condition can be used as an indicator of the level of service. For example, the average road condition can be tied to road safety and comfort.

4.2 Can this data influence decision-makers?

It is important for any metrics, not just equity-based analysis, to be geared towards influencing decisions. Examples of facilities whose locations are not influenced by community demographics include localized facilities such as museums or homeless shelters, very large facilities such as major stadiums, arenas, or sportsplexes, or facilities that are related to natural infrastructure such as beaches. It is essential to note that caring for these assets at large is important, but an LOS such as "travel distance to the closest stadium from equity deserving neighborhoods" is unlikely to impact the decision of where to build a new stadium.

Another example of LOS that would fail this metric is when the decisions influenced by the LOS are made at large and cannot be influenced by socioeconomic factors. An example would be "# of kilometers of storm network CCTV inspected annually" from the City of London's stormwater asset management plan (City of London 2023). A decision on whether a pipe is inspected stems mainly from the pipe's age/useful life or whether previous breaks were frequent and is not related to the income level of the neighborhood where the pipe is located. However, an LOS related to the condition of the pipes within different neighborhoods might be worthy of investigation.

5. DATA ANALYSIS: ASSESSING SOCIAL EQUITY

Omer (2006) proposed five dimensions to measure social equity, linking it to the degree of resource distribution across different regions, incomes, and ethnic groups. The definition has evolved over the years and branched into two main schools of thought. Horizontal Equity states that each group should receive the same benefits and bear the same costs, regardless of their needs (Behbahani et al. 2019; Litman 2022). Vertical Equity, on the other hand, deals with fairness and encourages the distribution of resources based on needs (Isais et al. 2016; Duran Rodas et al. 2020). One can argue that municipalities and large asset owners already consider social equity in maintaining their portfolios, focusing on the "best bang for their buck" across the entire network. The focus of this paper, however, is exploring vertical equity metrics where the infrastructure performance in disadvantaged neighborhoods is compared to that across the rest of the network. Kothari et al. (2022) have provided a comprehensive list of different metrics to assess both vertical and horizontal equities. The focus of this paper is on developing the framework where some of these metrics can be applied. As such, the main concern here is the quality of the data which can be summarized in the two questions mentioned in Fig. 1 (Can the impact be localized? And is the data granular enough?). Each of these two questions will be discussed in greater detail in the following subsections.

5.1 Is the data granular?

According to Omer (2006), infrastructure data and economic attributes are often available in varying degrees of granularity. Hence, a tradeoff needs to be considered where one of the datasets has to be aggregated. For example, to a municipality, the condition of every street is known, while the economic attributes of the households on that particular street can only be assumed. Therefore, the infrastructure conditions are often aggregated to a level where they can be properly correlated to the socio-economic data available (e.g., census tract or neighborhood level).

This becomes a bigger problem when the granularity of the community data is higher than that of the infrastructure performance metrics. For example, municipalities often produce water quality reports. However, these reports are often produced based on tests performed at the main treatment plant. Hence, an overall water quality is assumed for the entire population utilizing the treatment plant. In the case of Flint, Michigan, for example, it is known that the water quality across the city is at a certain level. This is useful information if the intention is to compare Flint to other cities that have different water sources. But if the population under analysis (Q1 in Fig. 1) is the people of Flint, Michigan, then comparing water quality across different neighborhoods can be challenging in the absence of proper tools. A similar LOS that might not be feasible to track within a community is the number of boil water advisories. While some advisories can be localized since their source can be easily identified such as local pumping stations, many advisories are issued either because of a problem in the central system or with main transmission pipes. In that case, identifying the population affected by these advisories becomes challenging. With the objective of LOS being metrics that are trackable over time, putting a neighborhood-level equity lens on these metrics becomes infeasible.

5.2 Can the impact be localized?

Similar to the point raised earlier, tracking the performance of centralized facilities for equity purposes is impractical. The city can be reliant on only one water or wastewater treatment plant, or having a distinct set of bridges that connect it to neighboring areas. Attempting to link these high-impact assets to the neighborhood where they are physically located ignores the city-wide impact that these assets have. Therefore, a metric such as "condition of the main water treatment plant" cannot be analyzed from an equity perspective.

6. DATA PRESENTATION

Finally, the results of these analyses can be presented in different ways depending on the level of granularity required. At a very high level, the performance metrics can simply be reported for neighborhoods with strong equity concerns as numerical values. These values are then compared either with the overall city performance or just the performance of the neighborhoods that do not share the same equity concerns.

The second method can help further identify performance gaps without concerns about the underserved neighborhoods heavily affecting the overall city-wide performance.

A more granular method of representation can be on a map as seen in Fig. 2. In Fig. 2, the neighborhoods are colored based on whether they are socioeconomically disadvantaged, while the size of the circle shows the infrastructure performance. While Fig. 2 shows only two categories for equity concerns and infrastructure performance, the analysis (and the accompanying presentation) can be done on more than two categories if the asset owners please. This representation allows for more succinct analysis and discussions (e.g., where the pockets of strong concerns are located), but can be too detailed for the viewers to handle and utilize for decision-making, especially if the representation shows too many categories.

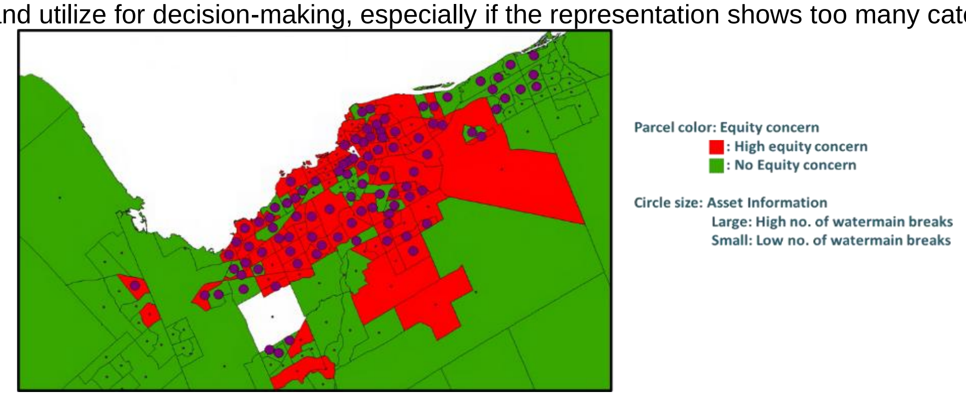

Fig. 2 Map Representation of Infrastructure Performance vs. Neighborhood Equity Concern

7. SUMMARY AND CONCLUSION

Social equity is an important component in analyzing the performance of an infrastructure portfolio to guide future growth or maintenance and rehabilitation decisions. However, the literature regarding performing equity-based infrastructure performance analysis is still in its infancy. The same can also be said of current industry practices. In this paper, we aim to provide a framework for conducting such analysis, considering the availability of the data and its structure. The developed framework discussed fundamental questions raised by researchers on how social equity can be incorporated into infrastructure performance analyses and then provided simple yes/no questions to help determine which performance metrics can be analyzed with an equity lens based on the available data.

When it comes to interpreting the analysis results, it is important to understand that the equity analysis is meant to complement, not replace, city-wide LOS already being established and monitored. For example, even if neighborhoods with high equity concern showed a relatively lower infrastructure performance metric. The focus should remain on neighborhoods. They can be considered to be well-served if the current performance is above the performance targets set by the asset owners. Instead, the focus should be on parts of the city that are below the predefined targets, regardless of their demographic attributes.

Similar to overall infrastructure indices such as the ASCE infrastructure report card. An overall index might mistakenly showcase that the neighborhood is equitably served if it has a mix of overperforming and underperforming infrastructure metrics. Hence, it is important to examine the different infrastructure metrics separately. The neighborhood that scored low on road condition should be the target of future investments in road rehabilitation projects, while the neighborhood that scored low on water service should be the target of future water service improvements. Prioritizing such cross-asset tradeoffs is the subject of a more detailed discussion that considers variances between neighborhood performance and city-wide or targeted performance, risks of infrastructure failure, and others.

In the absence of equity-related public consultations, the proposed framework is a good way to move forward since it relies on data already being collected during normal operations. Hence, future work is investing in community conversations and public consultations targeted at the underserved communities to properly understand what services they are looking for the government to provide as well as their perception of the current and desired service levels.

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