Quantitative Measures of Social Sustainability for Pavements. Future Directions for Implementation.

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Abstract. Pavement sustainability requires balancing economic, environmental, and social factors. Yet, the social aspect is often less studied and harder to measure, making its integration into life-cycle approaches complex. Recent policies like the Justice40 initiative and the bipartisan infrastructure bill have highlighted the necessity for fair infrastructure, emphasizing the importance of concrete social sustainability measures. Current methods like social life cycle assessment (S-LCA) tend to concentrate more on social governance and human well-being, rather than provid-ing a tangible measure of how pavement investments affect individuals. This research summa-rizes a new method to measure the effects of road conditions on marginalized groups, particu-larly Environmental Justice (EJ) communities. It stresses the need to include social factors in as-sessing pavement sustainability. This approach evaluates the impact of road conditions on both EJ and non-EJ community members and road users. It examines fuel usage during commutes in relation to pavement quality in these areas. Finally, the study discusses future research direc-tions for the methodology's usage in life cycle frameworks such as LCA and LCCA.

Keywords: Social Sustainability, Environmental Justice, LCA, LCCA, S-LCA.

1 Introduction

Transportation significantly contributes to greenhouse gas emissions in the U.S., accounting for approximately 29% of total emissions (United States Environmental Protection Agency, 2022). Pavements, essential for supporting both freight and personal vehicles, are integral to the sustainability of the transportation system (Hu et al., 2021; Federal Highway Administration, 2020). Pavement sustainability encompasses a broad range of objectives, including achieving engineering goals, preserving ecosystems, using resources economically, and meeting basic human needs such as health, safety, equity, employment, comfort, and happiness (Van Dam et al., 2015). This concept aligns with the triple-bottom line approach, which focuses on economic, environmental, and social sustainability (Fulzele et al., 2019).

While the economic and environmental dimensions of pavement sustainability have been extensively studied and can be quantified through methodologies like Life Cycle Cost Analysis (LCCA) and Life Cycle Assessment (LCA) (Okte et al., 2019; Mallela & Sadavisam, 2011; Chan et al., 2008), the social aspect remains relatively understudied. Assessing social sustainability requires the development of metrics to quantify the impact of pavement design, rehabilitation, and maintenance decisions on communities, especially those disproportionately facing negative impacts (Conceição & Ferreira, 2000; Gardner, 2021; Kothari et al., 2022; France-Mensah et al., 2019; Kothari, 2022; Logan & Guikema, 2020). This study builds upon recent work in pavement sustainability and transportation equity by focusing on disadvantaged communities that are often burdened with poor road conditions and by exploring methodologies to quantify their impact during essential recurring trips, such as home-to-work journeys.

2 Goal and Scope

This paper summarizes a methodology (Okte et al, 2024) that quantitatively describes and measures the impact of road conditions on vulnerable communities, emphasizing the importance of considering the social component in pavement sustainability assessment. Finally, future research directions are discussed for follow-up studies. Massachusetts serves as the case study area. The methodology aims to integrate social sustainability considerations into existing life-cycle methodologies. The outline of the study is as follows:

1. Summary of Okte et al 2024 methodology
    a. Obtaining pavement condition from geo-MassDOT
    b. Overlaying pavement condition with vulnerable communities
    c. Matching communities to their work locations to find recurrent trips
    d. Comparing the pavement condition and fuel consumption within and outside EJ communities to assess if the pavement infrastructure serves everyone equally.
2. Discussion of implementation for future studies

3 Methodology

3.1 Defining Vulnerable Communities (EJ for Massachusetts)

Environmental Justice (EJ) communities in Massachusetts were defined using specific criteria set by the Massachusetts Department of Transportation, based on U.S. Census data. These criteria include a community being identified as an EJ community if it meets any of the following conditions: the annual median household income is 65 percent or less of the statewide median, minorities comprise 40 percent or more of the population, 25 percent or more households have limited English proficiency, or minorities make up 25 percent or more of the population in a municipality where the median household income does not exceed 150 percent of the statewide median (Massachusetts Department of Transportation, 2022; US Census Bureau, 2022).

3.2 Assessing Road Conditions and Excessive Fuel Consumption

In assessing road conditions in Massachusetts, the study used the Present Serviceability Index (PSI) to evaluate 5967 miles of state-owned roads. The PSI, a measure of road quality based on factors such as cracking and rutting, ranges from 0 to 5, with higher values indicating better road quality. Roads were categorized as excellent, good, fair, or poor based on their PSI scores. To quantify the impact of road conditions on travel, the study employed the International Roughness Index (IRI), a measure of road roughness. By converting PSI values to IRI, the study estimated excessive fuel consumption due to varying road conditions, particularly focusing on their impact on Environmental Justice (EJ) and non-EJ communities in Massachusetts (Paterson, 1986; Ziyadi et al., 2018). Figure 1 summarizes this analysis.

3.3 Analyzing Home-Work Trips

Home-work trips in Massachusetts were analyzed using the LEHD Origin-Destination Employment Statistics (LODES) from the U.S. Census Bureau, focusing on the main trips of residents living and working within the state as of 2019. This data, encompassing approximately 3.02 million trips by over 3.31 million people, identified residents in EJ block groups as part of EJ communities. The study constructed a road graph to find the shortest travel paths, excluding trips under 5 miles to focus on those likely taken by personal vehicle. The analysis then calculated the excessive fuel consumption (Ziyadi et al, 2018) for these trips, comparing the impact on EJ and non-EJ communities. Figure 2 provides an example trip calculation.

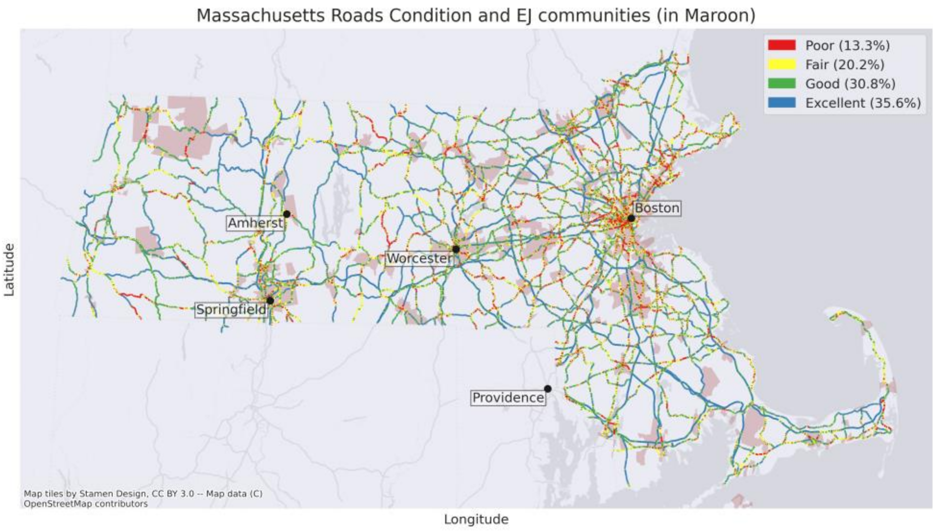

Figure 1 EJ communities overlaid with road condition in Massachusetts.

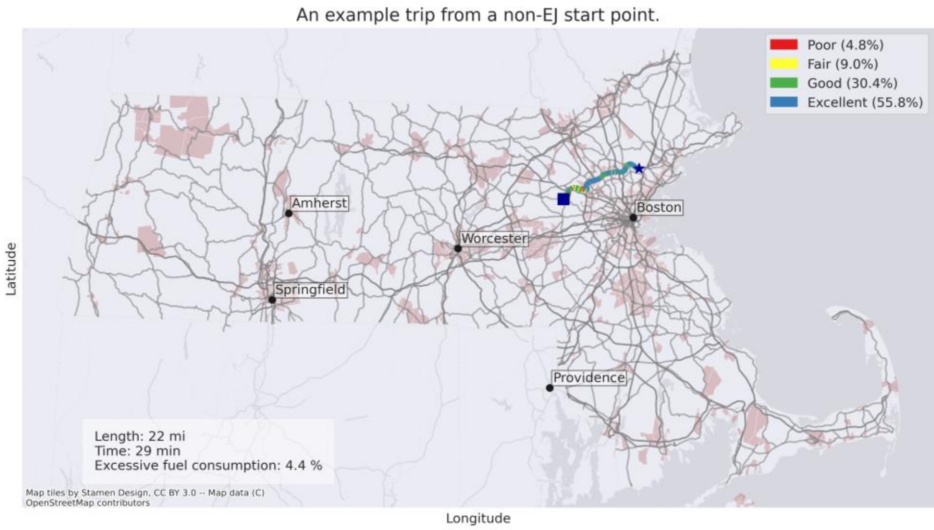

Figure 2 Example of home-work trip calculation

4 Assumptions and Limitations

The study assumed that all trips follow the MassDOT managed road network, with the acknowledgment that while local roads outside of MassDOT jurisdiction exist, most trips longer than 5 miles are likely to include major routes and interstates. Another assumption was that all trips over 5 miles are possible by personal vehicle, noting that the LODES data does not include travel mode information, thus precluding the separation of personal vehicle trips from public transportation. Lastly, the study recognizes that there are multiple user impacts such as maintenance, repair, and tire wear-and-tear that are influenced by factors like IRI, vehicle type, and localized distresses like potholes. In this study, however, only energy consumption was utilized as an indicator to demonstrate the impact of road condition on users as an illustrative example (Liu & Al-Qadi, 2023; Kim et al., 2017)

5 Summary

This study summarizes a methodology for evaluating the disproportionate impact of road conditions on disadvantaged communities, highlighting the need for metrics to quantify these inequalities (Okte et al, 2024). Findings indicate that within the entire state of Massachusetts, EJ communities are nearly twice as likely to live near poor roads and consume up to twice as much excessive fuel due to road conditions.

6 Future Work

6.1 Vulnerable community definition

There are various future research directions. First, it is crucial to define vulnerable communities of interest. For instance, although EJ was used for Massachusetts, different states may use different definitions of vulnerable communities. Moreover, because vulnerable communities are usually a collection of different categories, it may be crucial to look at different sub-categories. For instance, Figure 3 shows the different EJ categories based on the definition of EJ communities in Massachusetts. Depending on the priorities of the analysis type, a study could focus on one or more EJ categories.

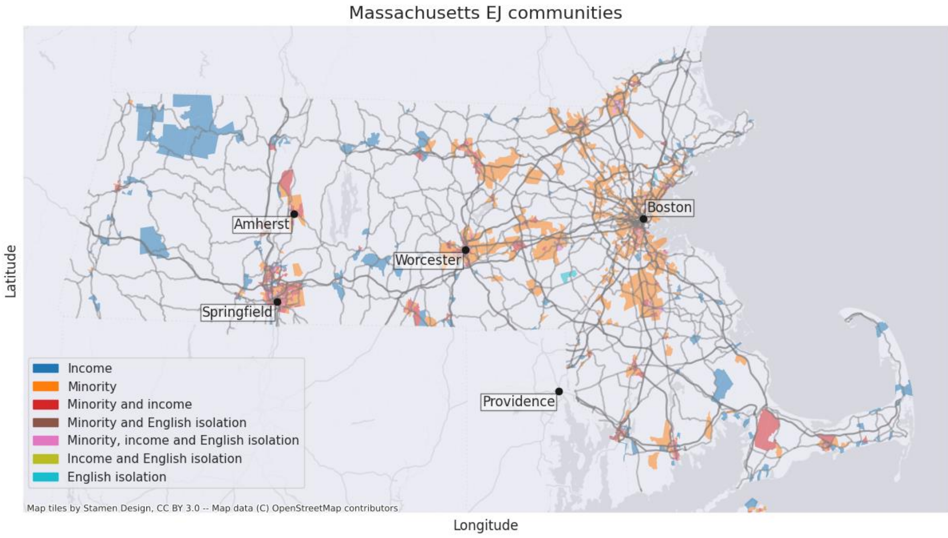

Figure 3 Example of home-work trip calculation

6.2 Definition of study area.

This analysis is by default, a network level analysis. Therefore, it is crucial to define the study area based on the responsible agency. For instance, this analysis could be conducted at a higher granularity for a township, but then the focus should be on the roads that that township is responsible for maintaining, similar to pavement management systems. It is also crucial to engage the responsible agency during or prior to analysis to better understand their needs and priorities. For instance, while this study used public MassDOT datasets to just introduce a methodology, future studies will engage MassDOT to see if they have specific goals/study areas in mind for implementation of this framework.

6.3 Investigation of other impacts

This study focused on road condition and additional fuel consumption as proxies for social sustainability. However, there could be other metrics of interest that an agency analyst may be interested in. For instance, this study used categorized road condition (Poor, Fair, Good, Excellent) as measures. However, pavement condition is usually on a continuous scale as shown in Figure 4. Categorizing the measures may hide existing trends in the distribution.

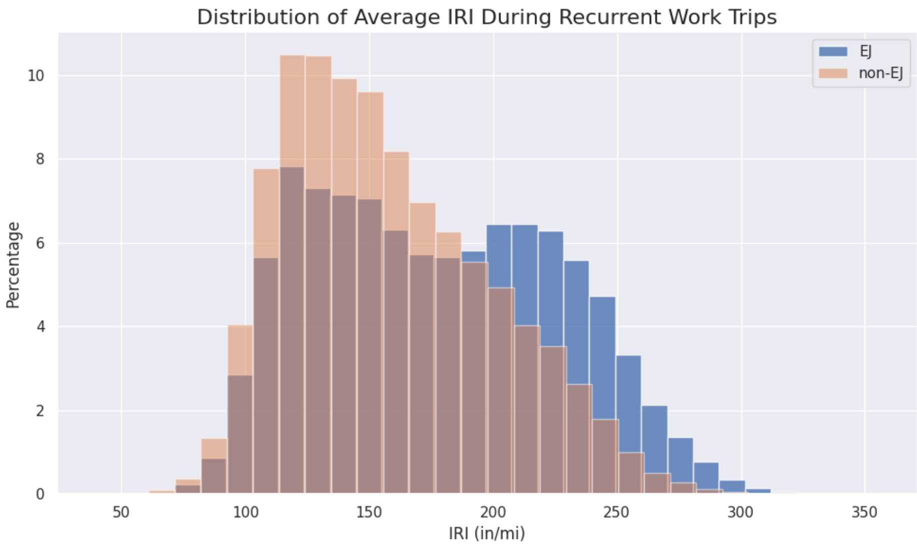

Figure 4 Distribution of IRI during recurrent home-work trips.

Moreover, there are many other social impacts that could be relevant to this analysis such as noise, particulate matter, vehicle operation and repair costs, work-zone disruptions, etc. that may be salient. While proxies are usually selected for analysis, it is important to pick proxies that cover a wide range of impacts (for instance IRI covers a wide range of user costs).

6.4 Implementation into life cycle frameworks

While this study only measures the impact, future research will also focus on how to assess different pavement management strategies for their performance in social sustainability. One possible direction is using a Lorenz curve and measures like the Gini coefficient and the Theil index to assess inequality within a distribution. The Lorenz Curve is a graphical representation that shows the distribution within a population. It plots the cumulative percentage of the population (on the x-axis) against the cumulative percentage of income or wealth that population holds (on the y-axis). A perfectly equal distribution would be a straight diagonal line from the bottom left to the top right corner, known as the line of equality. The Gini Index, or Gini coefficient, is a numerical measure derived from the Lorenz Curve, ranging between 0 and 1, where 0 represents perfect equality (everyone has the same income or wealth) and 1 represents perfect inequality (one person has all the income or wealth, and everyone else has none). It quantifies the discrepancy or inequality in a distribution, making it a useful tool for comparing inequality across different populations or over time. Figure 5 shows the Lorenz curve for travel in excellent roads for Massachusetts population. A maintenance schedule's performance could be investigated by looking at how the Lorenz curve and related indices change before and after the maintenance.

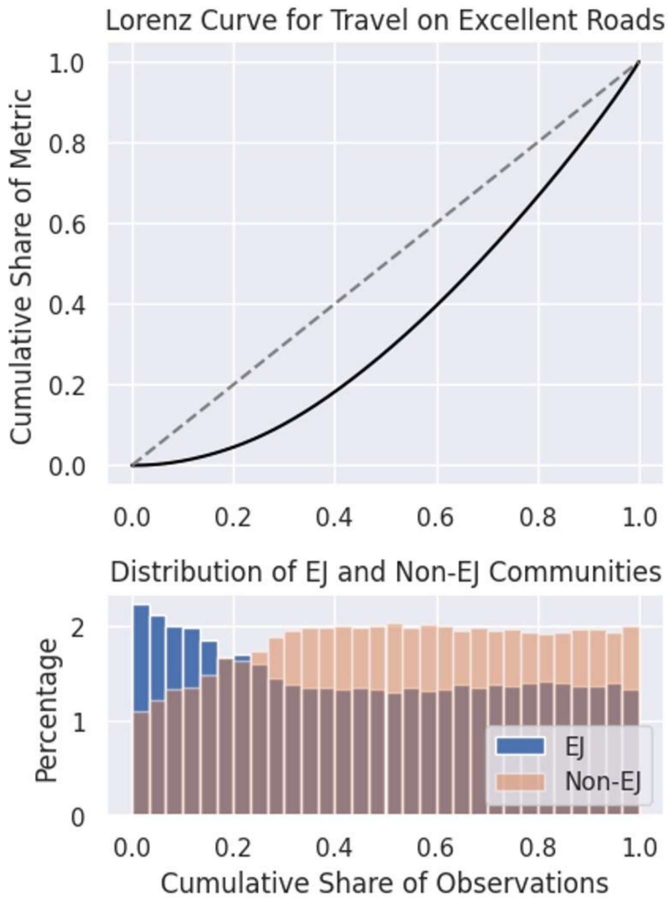

Figure 5 Lorenz curve for EJ and non-EJ communities

Finally, future studies should also consider incorporating the impact of road conditions on the health of nearby residents. This involves considering factors like traffic volume and road proximity, which can be analyzed at more detailed resolutions, such as county, city networks, or individual road sections. In Life Cycle Cost Analysis (LCCA), although user costs (including emissions, safety, delay, etc.) are sometimes calculated, they are usually aggregated for all users. Implementing inequality measures could allow these costs to vary within LCCA. Similarly, in Life Cycle Assessment (LCA), the usage stage could incorporate an inequality measure for different alternatives, in addition to total emissions. Although LCCA and LCA are effective for quantifying economic and environmental impacts, they often fall short in capturing impacts that are not easily quantifiable in monetary terms or emissions.

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