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Equity in Transportation Asset Management: A Proposed Framework

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Abstract: Transportation asset management has historically overlooked equity considerations. However, recently, there has been a significant increase in concerns about this issue, leading to a range of research and practices aimed at achieving more equitable outcomes. Yet, addressing equity is challenging and time-consuming, given its complexity and multifaceted nature. Several factors can significantly impact the outcome of an analysis, including the definition of equity, the evaluation and quantification of its impacts, and the community classification. As a result, there can be a wide range of interpretations of what constitutes equity. Therefore, there is no single correct or incorrect approach for equity evaluation, and different perspectives, impacts, and analysis methods could be considered for this purpose. This study reviews previous research on how transportation agencies are integrating equity into transportation asset management, particularly pavement management systems. The primary objective is to investigate important equity factors for pavement management and propose a prototype framework that integrates economic, environmental, and social equity considerations into the decision-making process for pavement maintenance, rehabilitation, and reconstruction projects. The proposed framework consists of two main steps: (1) defining objectives based on the three equity dimensions, and (2) analyzing key factors for identifying underserved areas through a case study approach. The case study analyzed pavement condition and sociodemographic data for California's Bay Area. Statistical analysis and a machine learning method revealed that areas with higher poverty rates and worse air quality tend to have poorer pavement conditions, highlighting the need to consider these factors when defining underserved areas in Bay Area and promoting equity in pavement management decision-making. The proposed framework incorporates an optimization problem to simultaneously minimize disparities in pavement conditions between underserved and other areas, reduce greenhouse gas emissions from construction and traffic disruptions, and maximize overall network pavement condition subject to budget constraints. By incorporating all three equity aspects into a quantitative decision-support framework with specific objectives, this study proposes a novel approach for transportation agencies to promote sustainable and equitable asset management practices.

Keywords: equity; asset management; pavement decision-making; resource allocation

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1. Introduction

Transportation asset management significantly impacts various aspects of modern society, including mobility, health, safety, economic opportunities, and overall life quality. Decision-making is a very important step in asset management, as it involves a wide range of activities, including strategic planning, infrastructure design, treatment selection, and policy implementation. At the core of these impacts lie well-functioning transportation systems, which comprise infrastructure, vehicles, regulations, and user behavior, all of which interact to meet travel demand within a specific area [1]. Distress detection is one of the most critical topics in this domain. As transportation assets inevitably deteriorate over time due to various factors, including traffic loads and environmental conditions, efficient and timely inspection is a crucial element of a successful infrastructure management system [2]. Effective asset management requires a meticulous decision-making process, which includes identifying current problems; establishing objectives, criteria, and constraints; creating solutions, such as new infrastructure construction; rehabilitating existing assets; and implementing management strategies.

The global cost of maintenance and repair for transportation infrastructure is remarkably high, amounting to hundreds of billions of USD annually. Numerous studies have consistently highlighted the detrimental impact of deteriorated transportation assets, such as pavements and bridges, on both public safety and economic productivity. A primary focus for researchers in this field is to minimize the substantial expenditures associated with inspection and maintenance efforts [3,4].

The complexity of decision-making intensifies when considering the multitude of stakeholder objectives, which often conflict. Highway agencies face the challenge of developing effective maintenance and rehabilitation (M&R) plans that accommodate limited funding and diverse stakeholder priorities. In transportation asset management, a wide range of stakeholders emerge, each representing distinct entities with varying objectives and vested interests. These stakeholders include local agencies overseeing highway infrastructure, highway users like commuters and businesses, environmental organizations advocating for ecological considerations, and local communities directly impacted by highway planning and operation. With such a diverse array of perspectives and priorities, decision-making processes require strategic coordination to address potential conflicts and maximize overall outcomes to provide an equitable system. Robust evaluation methods are crucial to achieving this balance by enabling a comprehensive assessment of trade-offs between various stakeholder priorities [5–7].

An effective transportation asset management program relies on various evaluation methods. These approaches differ in how they handle weight definition and analysis. In the field of transportation asset management, evaluation methods can be broadly categorized into parametric and non-parametric approaches, each with distinct implications for weight definition and analysis. Parametric methods, such as Stochastic Frontier Analysis (SFA), assume a specific functional form for the relationship between inputs and outputs, with weights often determined exogenously based on theoretical or empirical considerations. In contrast, non-parametric methods like data envelopment analysis (DEA) do not assume a specific functional form, deriving weights endogenously from the observed data. This allows for a flexible evaluation of efficiency without predefined weights. Multi-criteria decision-making (MCDM) approaches often fall into the parametric category, with exogenously defined weights [8].

The United States has recently made significant investments in its highway infrastructure network to enhance sustainable development within the country. These extensive investments have resulted in the development of over 8 million lane miles of urban and rural roads throughout the country [9–13]. Sustainable development includes economic, environmental, and social aspects of decision-making. These dimensions may have conflicting relationships, requiring a balance based on decision-makers' preferences [14,15].

In the economic dimension, highway agencies aim to make cost-effective decisions for M&R plans within limited budgets [16]. According to Title 23 of the United States Code, the second aspect is concerned with the environmental dimension [17]. It considers greenhouse gas (GHG) emissions in M&R projects and aims to protect the natural environment while improving transportation systems. Environmentally friendly approaches may not always be the most cost-effective, and there should be a tradeoff between these dimensions [18–22]. Moreover, the Federal Highway Administration (FHWA) introduced a third aspect in the asset management practices of decision-making as social equity, which focuses on social responsibility and equity in the highway M&R process [23]. Developing sustainable M&R plans poses significant challenges for decision-makers, who must consider multiple conflicting objectives. Therefore, social equity is often overlooked as decision-makers mostly focus on the economic and/or environmental aspects [24–27]. By distributing benefits fairly and equitably among all stakeholders, decision-makers can ensure that the transportation system meets the needs of all members of society, regardless of their background or location.

While there has been growing recognition of the importance of equity in transportation asset management, a limited number of studies have comprehensively explored its integration into decision-making processes. Existing research primarily focuses on individual aspects of equity, such as social equity or environmental justice, within the context of pavement maintenance optimization; however, these studies often rely on specific assumptions or lack consensus on how to best measure equity. For instance, in 2009, Thomopoulos et al. [28] proposed a method for evaluating the equity impacts of transportation infrastructure projects. The indicators used in this study are assumed to accurately reflect and measure the equity impacts of the project, even though there is no consensus on the most suitable indicators for assessing various aspects of equity. As a result, there is a possibility that the results may have been biased. In 2015, Boyles [29] conducted research to incorporate equity considerations into a network-level maintenance optimization problem. The study assumed the pavement deteriorates over time and can only be maintained through a single maintenance action, with the maintenance intervals for each facility identified as decision variables, subject to an annual budget constraint. This study made significant contributions to the field by incorporating equity considerations into a network-level pavement maintenance optimization problem. However, it is important to note that the assumptions made about the cost of maintenance, discount rate, and usage rates of facilities may not reflect real-world conditions.

In another study, in 2018, France-Mensah et al. [30] compared three methods including ranking-based, integer linear programming (ILP), and decision tree with needs-based allocation (DTN) [31] for the budget allocation of pavement M&R projects in a subset network in Texas. Following this research, they [32] conducted another study in 2019 to evaluate four different policies for incorporating social equity in highway M&R decision-making. For this purpose, they developed budget allocation models for each policy and used genetic algorithms (GA) to obtain policy-specific optimal solutions. Finally in 2022, Kothari et al. [23] proposed a sustainable pavement management plan, which considered all three aspects of sustainability, including economic, environmental, and social equity.

Gunathilaka and Amarasingha [33] also developed a framework based on the analytic network process (ANP) method for prioritizing pavement maintenance and rehabilitation projects considering social and economic factors, in Sri Lanka. The key factors in this research for equity evaluation were road user satisfaction, social equity, economic growth, environmental sustainability, road safety, technical feasibility, and project cost. Pairwise comparison interviews were conducted with nine transportation experts, and the obtained weights were converted into a matrix to obtain priorities.

Traditional approaches to incorporating equity often struggle to account for the inherent uncertainties in transportation planning. These uncertainties can stem from factors like population growth, traffic patterns, and economic fluctuations. As a result, achieving a truly balanced distribution of benefits across network users can be challenging. In 2017, Caggiani et al. [34] proposed a novel approach to address this limitation. They advocate for a paradigm shift towards incorporating flexible equity constraints represented by fuzzy sets. Fuzzy sets acknowledge and quantify these uncertainties, allowing for a more nuanced consideration of equity in decision-making. By introducing fuzzy programming, they achieved a more balanced distribution of benefits across network users, addressing both horizontal and vertical equity concerns.

Recent advancements in artificial intelligence and machine learning techniques present significant opportunities for optimizing decision-making processes in transportation asset management. Potential methods for optimization in this context include machine learning classifiers such as artificial neural networks (ANNs), random forest classifiers, and support vector machine (SVM) models. These models can address key optimization issues such as network capacity by enabling dynamic resource allocation, sample complexity by requiring fewer labeled data for training, and computational complexity through efficient learning algorithms. Additionally, genetic algorithms, integer linear programming (ILP), and the analytic network process (ANP) have been successfully applied in previous studies for similar optimization problems, highlighting their potential applicability in this framework [35].

When it comes to incorporating equity into transportation and infrastructure systems, it goes beyond just research. The FHWA developed PlanWorks as a tool to facilitate collaborative decision-making during transportation planning and project development [36]. PlanWorks provides guidance on how and when to involve cross-disciplinary partners and stakeholder groups, encouraging transportation professionals to consider environmental equity throughout the entire planning and project development process. While the FHWA has made commendable efforts to incorporate environmental justice (EJ) considerations into transportation planning, there is a need to explore how EJ can be integrated with other equity aspects in transportation planning. The United States Department of Transportation (US DOT) has also taken a significant step towards prioritizing equity as a core strategic goal. The aim is to promote equity across the department's policies and programs, with the ultimate goal of reducing transportation-related inequities within the communities they serve [37].

In another practice, the US Government Accountability Office (GAO) conducted research to investigate uneven National Highway System (NHS) pavement conditions in communities with different characteristics. The findings indicate that 3.7 percent of the pavement in census tracts with higher underserved racial and ethnic populations is in poor condition, whereas only 1.3 percent of the pavement in census tracts with lower underserved racial and ethnic populations is in poor condition. Additionally, the investigation found a significant association between the prevalence of family poverty in a census tract and the condition of the National Highway System pavement in that area. Census tracts with higher rates of family poverty had a higher percentage of pavement in poor condition and a lower percentage in good condition [38]. The results highlighted the importance of considering underserved areas as a factor in the decision-making process and asset management planning.

According to the literature, most studies tried to consider different aspects of sustainability to develop an equitable asset management program, while there are a limited number of studies covering all three factors simultaneously. The objective of this study is to develop a prototype decision-support framework for allocating budgets for asset management projects by integrating all three decision parameters. The scope of implementation of the framework includes pavement maintenance, rehabilitation, and reconstruction projects.

Following this comprehensive literature review, Section 2 details the proposed decision-support framework. This framework involves a three-step process: defining objectives, analyzing data to identify underserved areas, and incorporating equity considerations into budget allocation for asset management projects, specifically focusing on pavement maintenance, rehabilitation, and reconstruction. The framework is followed by a case study analysis to investigate key factors influencing pavement conditions in underserved areas and to help define the underserved areas for the framework. Results are represented in Section 3. Section 4 discusses the potential limitations and biases of the framework, providing a critical evaluation of its robustness and applicability. Finally, Section 5 concludes with a summary of the key findings and implications, emphasizing the importance of integrating equity into transportation asset management decision-making.

2. Materials and Methods

The schematic representation of the framework is demonstrated in Figure 1. Furthermore, an analysis was conducted based on a case study to investigate the important factors that must be considered in the decision-making process. In other words, the focus is on identifying and highlighting the key factors that have a significant impact on equitable asset management planning. The case study serves as a real-life example, illustrating how considering certain factors to define an underserved area can lead to more inclusive and equitable outcomes in transportation asset management. The implementation of the case study is discussed in the following paragraphs.

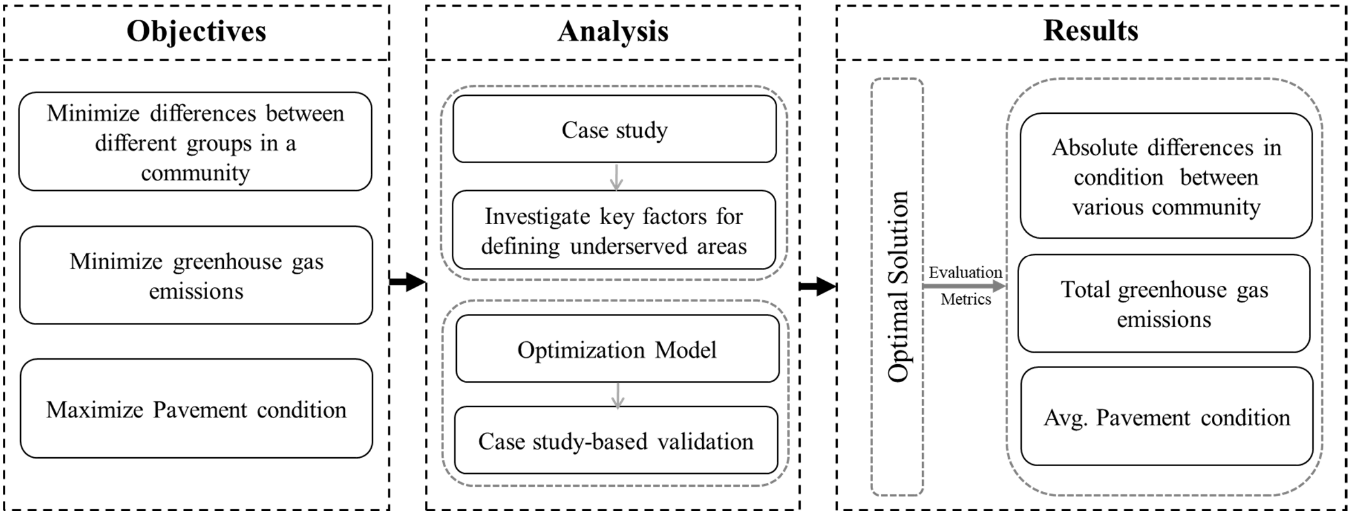


Figure 1. Schematic framework.

2.1. Framework

As shown in Figure 1, this framework consists of three steps. The first step involves defining the objective of the research. The second step deals with the analysis in which underserved areas are defined based on key factors, such as sociodemographics, using a case study approach. Then, the optimization model could be developed to select the best treatment option by optimizing the objectives. In the third and final step of the framework, the optimal solution obtained from the developed optimization model should be evaluated using the necessary evaluation metrics to demonstrate the efficiency and effectiveness of the chosen solution.

As previously discussed, the objective can be generally formulated as Equation (1), which is an optimization problem with three factors, including the economic, environmental, and social equity aspects, representing the three components of sustainable planning. The optimization technique proposed in this study to develop a sustainable pavement management plan is based on the literature [25].

$$M\&R\ option = f(SD, EN, EC) \tag{1}$$

where $M\&R\ option$ is the most optimum maintenance and rehabilitation activities; SD is sociodemographic factors; EN is environmental factors; and EC is economic factors.

Multiple factors such as type, measurement mechanism, and service provided can indicate the transportation asset performance with respect to a particular decision parameter. Regarding the focus of this paper, performance measurement is developed to assess pavements. In Equation (1), the first objective considers the social aspect and tries to enhance social equity by decreasing the condition gap between a disadvantaged group and others. The second objective focuses on the environmental aspect, with an emphasis on minimizing greenhouse gas (GHG) emissions [22]. Lastly, the third objective is about the economic aspect, which aims to reduce agency and road user costs by optimizing the road network condition [30]. A total number of 10 factors that affect the three decision parameters were used in this study based on the literature review, which is discussed in the following paragraphs.

2.2. Objectives

Pavement quality plays a significant role in ensuring smooth transportation flow and connectivity. Well-maintained pavements offer a smoother, safer, and more reliable transportation infrastructure system, which positively impacts daily activities, mobility, and access to essential services, including jobs, education, healthcare, and business opportunities. Therefore, every member of society has the right to access a good-quality pavement system. However, underserved communities often face greater challenges with the quality of their transportation infrastructure. In simple terms, underserved communities have less access to well-maintained and reliable infrastructure compared to other regions.

Previous studies [38] suggest investigating various parameters' relationships with pavement condition (PC), such as population density, percentage of elderly people, race and ethnicity, traffic, education level, poverty rate, and unemployment rate. Using the factors, underserved areas were defined, as the results showed significant differences in pavement quality in areas with varying percentages of these factors. By minimizing differences in pavement quality among different groups in a community, transportation systems become more efficient and interconnected, benefiting not only underserved areas but the entire community.

The first aspect of a sustainable pavement management system is social equity. Therefore, addressing these disparities by minimizing objective 1 ensures that all community members have access to safe and well-maintained pavements, promoting social inclusivity and cohesion. The objective function can be formulated as Equation (2).

$$Minimize\ Objective_1 = \textstyle\sum_{i=1}^{n} \displaystyle\sum_{j=1}^{m} \left| PC_{UA,i} - PC_{OA,j} \right| \quad (2)$$

where

$Objective_1$: Minimize the absolute difference in pavement conditions between underserved and other areas.

$PC_{UA,i}$ = Pavement condition in underserved areas.

$PC_{OA,j}$ = Pavement condition in other areas.

n = Number of underserved areas.

m = Number of other areas.

constraints:

$PC_{UA,i}, PC_{OA,j}$: *specified ranges based on agency requirements.*

Budget constraints.

The environmental aspect of the pavement management system is defined as the second factor in a sustainable system. Reducing air pollution is a critical consideration in pavement planning, as air pollution, especially GHG emissions, significantly contributes to climate change and negatively affects air quality and public health. Therefore, another objective of this study is to improve air quality by selecting treatment options that produce less GHG emissions from two sources: traffic disruptions, which are influenced by traffic volume and treatment duration, and emissions from construction activities, which depend on the type of applied treatment (Equation (3)) [23,32].

$$Minimize\ Objective_2 = E_{C,k} + E_{T,k} \quad (3)$$

where

$Objective_2$: Minimize the total emissions from construction and traffic disruptions.

E_C = Emissions from construction activities in kg CO_2 equivalents.

E_T = Emissions from traffic disruptions in kg CO_2 equivalents.

constraints:

Budget constraints.

Emissions limits.

Treatment feasibility and schedules constraints.

The emissions from construction activities ($E_{C,k}$ are dependent on the specific type of M&R treatment performed on a given road section. This component accounts for emissions generated from material production, transportation of materials and equipment, as well as the construction processes themselves. Consequently, M&R activities that are more extensive and intensive in nature will inevitably result in higher $E_{C,k}$ levels. This is due to the larger quantities of materials required and the longer durations of the construction projects, leading to prolonged usage of emissions-producing construction equipment. The $E_{C,k}$ can be quantified using the Equation (4) [23,32].

$$E_{C,k} = \sum_{i=1}^{N} \sum_{j=1}^{J} \sum_{t=1}^{T} (gc_{itj}) \tag{4}$$

where

gc_{itj} = the average GHG emission due to a specific M&R treatment type i on section j at time t.

Different scenarios can be defined for construction activities, including doing nothing, applying preservation treatments, implementing rehabilitation treatments, performing reconstructions, or conducting maintenance. Preservations are proactive treatments that aim to protect the existing pavement and extend its service life, resulting in lower construction emissions compared to more extensive rehabilitation or reconstruction methods. Rehabilitation treatments involve partial pavement restoration, requiring moderate construction emissions but leading to reduced traffic disruptions compared to full reconstruction. Reconstruction treatments involving complete pavement replacement typically result in higher construction emissions due to the extensive nature of the work. Maintenance activities address minor pavement issues and prevent further deterioration, potentially causing lower construction emissions, but may lead to increased traffic disruptions if not appropriately planned.

Emissions due to traffic disruption ($E_{T,k}$) are another critical factor to consider. Traffic disruption also refers to the inconveniences and disturbances caused to traffic flow and road users during construction activities. It can lead to significant traffic congestion, resulting in increased fuel consumption and adverse effects on air quality. Lane closures, road diversions, and reduced road capacity can create bottlenecks, causing vehicles to move too slowly. Consequently, cars consume more fuel than usual, leading to higher emissions of GHG and other pollutants. Reduced traffic flow efficiency due to congestion can further exacerbate air pollution, as vehicles spend more time on the road emitting pollutants. To address these issues, pavement management systems should carefully consider planning and scheduling activities to minimize the impact on traffic flow.

The $E_{T,k}$ is a function of the traffic volume and the duration required to apply the M&R treatment. It can be quantified using the Equation (5) [23,32].

$$E_{T,k} = \sum_{i=1}^{N} \sum_{j=1}^{J} \sum_{t=1}^{T} (gd_{itj}) \cdot AADT_{jt} \tag{5}$$

where

$AADT_{jt}$ = the expected annual average daily traffic on section j in year t.

gd_{itj} = the marginal increase in GHG emissions of treatment i due to traffic disruptions on section j at time t for each unit of $AADT$.

Based on previous studies, the unit costs for the scenarios and their estimated GHG emissions from construction and traffic disruptions are included in Table 1, which serves as a schematic table for this [19,23,39].

The third aspect of sustainability is the economical point of view, in which pavement condition plays a vital role. Pavement condition assessment relies on various indicators or indices that reflect its overall state or level of service. These include pavement structural condition indicators such as the pavement structural number and distress score, as well as pavement functional condition indicators like the International Roughness Index (IRI) and riding quality. There are also indicators that combine both structural and functional conditions, such as the Pavement Condition Index (PCI) and Pavement Condition Rating (PCR). While different state Departments of Transportation (DOTs) use various pavement condition indices based on their own policies and the data they collect in their pavement management systems, the PCI provides a standard way to assess pavement condition. It is a scored metric ranging from 0 to 100, where 0 indicates the most severe pavement deterioration and 100 represents the optimal pavement condition. In this study, the PCI is employed as the primary indicator for assessing pavement condition. The PCI is chosen due to its comprehensive coverage of all significant distress factors for pavements, including rutting, roughness, and cracking. This index is calculated using mathematical formulas, providing a complete picture of pavement condition and facilitating effective evaluation of pavement performance in different situations [40].

Table 1. Schematic Table for Environmental Analysis [23].

Treatments	Construction Emission (kg CO2eq = lane − mi)	Traffic Emission (kg CO2eq = lane − mi − AADT)	Agency Costs ($/lane − mile)
Do Nothing	0	0	0
Preservation	5700	0.5	37,000
Rehabilitation	28,000	2.5	300,000
Reconstruction	57,000	5.1	560,000
Maintenance	17,000	1.5	220,000

Over time, pavement sections deteriorate, leading to a reduction in their condition. However, implementing the appropriate M&R treatments at the right time could improve the pavement condition significantly, thereby reducing both agency and user costs. This is because well-maintained pavements exert less pressure on vehicles, resulting in reduced deterioration and increased vehicle service life, consequently lower maintenance costs for vehicle owners. Additionally, smoother pavements enhance fuel efficiency, reducing fuel consumption and associated expenses for drivers. On the other hand, deteriorated pavements can lead to increased vehicle operating costs, frequent repairs, and potential accidents due to uneven road surfaces.

Moreover, for agencies responsible for maintaining and managing road networks, the condition of pavements directly impacts their operational costs. Regular and timely maintenance of pavements can prevent minor issues from escalating into more severe problems, thereby reducing the need for expensive repairs and reconstruction. By optimizing the pavement condition through appropriate M&R strategies, agencies can effectively extend the service life of the pavement, maximizing their return on investment. On the other hand, neglecting pavement conditions can lead to premature failure, requiring costly emergency repairs and increasing the burden on the agency's budget.

Therefore, maximizing the pavement condition, as demonstrated in Equation (6), is an important objective from an economic efficiency standpoint. This not only translates to cost savings for both users and agencies over the long term but also ensures that budget allocations are utilized effectively by prioritizing the sections that require immediate attention based on their current condition and expected performance.

$$Maximize\ Objective_3 = \frac{1}{T} \times \sum_{t=1}^{T} PC_t \tag{6}$$

where

$Objective_3$: Maximize the average pavement condition over a given period.
PC_t = Pavement Condition at time t.
T = Total period of analysis.
constraints:
Pavement condition limits.
Treatment feasibility and schedules constraints.
Budget constraints.

2.3. Analysis

In the analysis section of this framework, the identification of underserved areas relies on sociodemographic key factors, including age, population density, poverty rate, and other mentioned variables. Employing a case study approach, the authors investigate whether there is a lack of equity in the decision-making process by assessing if certain communities or regions are suffering from worse pavement conditions in comparison to others.

Case Study

A comprehensive dataset was used as a case study in this research. The data was publicly available, containing sociodemographic data for California's Bay Area, sourced from the Office of Environmental Health Hazard Assessment (OEHHA) (The Office of Environmental Health Hazard Assessment 2023), alongside 20,764 miles of local pavement condition data obtained from the metropolitan transportation commission (MTC) website [41]. The dataset contains 1584 census tracts and is used as a resource to explore which significant factors should be considered in the decision-making process for pavement management and define underserved areas. Table 2 summarizes the dataset used in the research.

Table 2. California's Bay Area data summary.

Data	Description
Pavement Condition	20,764 miles of local roads Source: Metropolitan Transportation Commission (MTC) website
Sociodemographic	1584 census tracts Source: Office of Environmental Health Hazard Assessment (OEHHA)

According to this dataset, 43% of the street pavement (length) in the Bay Area is in excellent condition, with a pavement condition index (PCI) of 80 or higher. Moreover, 28% falls under the category of good condition, with a PCI ranging from 79 to 60. Furthermore, 9% of the pavement is considered to be at risk, with a PCI between 59 and 50, while 20% is classified as poor condition, with a PCI of 49 or lower. Figure 2 represents the distribution of pavement condition across the California Bay Area.

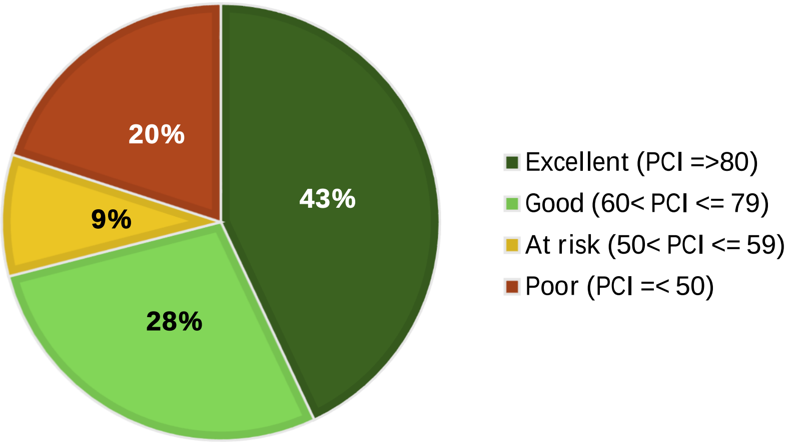


Figure 2. Pavement condition distribution in California's Bay Area.

According to the sociodemographic data, the total population in the area is around 7,758,000, with only 7.5% of individuals over 25 years old having less than a high school education, almost 60% of the population are not classified as white, and almost 14% are aged 65 and older. The dataset was then analyzed to investigate any relationships between pavement condition and various factors, including educational level, traffic, air quality, race and ethnicity, age, income level, and population density. Initially, a non-parametric approach was employed to identify key factors influencing pavement quality in underserved areas. This exploratory phase prioritizes data-driven insights, allowing for a flexible analysis of efficiency without predefined weights. This approach is particularly well suited for uncovering complex relationships between various sociodemographic factors and pavement condition.

A statistical analysis was initially conducted, followed by the application of the Lasso (least absolute shrinkage and selection operator) regression method for more precise predictions and a better understanding of the impact of these factors on pavement condition. The detailed results are presented in Tables 3 and 4 in the result section.

The second step of analysis in this framework involves developing an optimization model that can solve Equation (1). This model for selecting maintenance and rehabilitation (M&R) options transitions to a parametric approach. The specific objective functions will be defined to quantify social equity, environmental impact, and economic efficiency. The weights for these objectives are determined exogenously, based on the established literature, policy considerations, and sustainability criteria.

The proposed framework incorporates objective constraints and regulations into the optimization process to ensure the proposed solutions are not only optimal but also feasible within the context of existing regulations and practical limitations. These constraints are derived from federal and state-level guidelines, standards, and regulations related to social equity, environmental justice, and sustainability considerations in transportation asset management. For instance, guidelines from the Federal Highway Administration (FHWA) and the Environmental Protection Agency (EPA) can be integrated as constraints to ensure compliance with environmental justice principles, air quality standards, and other relevant regulations. Additionally, state-level regulations and local ordinances specific to the region under consideration can be included as constraints, addressing factors such as minimum accessibility requirements for underserved communities, maximum allowable emissions levels, or specific criteria for defining and prioritizing disadvantaged areas. The constraints may also include budget limitations, an acceptable pavement performance range, and limitations on the frequency of M&R treatments applied to a pavement section. By incorporating these regulatory constraints, the framework ensures that any proposed solution adheres to established guidelines and standards, reducing subjectivity and distortion due to stakeholder perceptions or regional peculiarities. The final step in this framework involves reporting the results and defining evaluation metrics to assess the efficiency of the model based on a case study dataset.

2.4. Excepted Output

In the third and final step of the framework, the optimal solution obtained from the developed optimization model should be reported. However, it is worth noting that this does not mark the conclusion of the process; evaluation metrics are necessary to demonstrate the efficiency and effectiveness of the optimum solution. These evaluation metrics play a pivotal role in measuring the equity in the optimized version of pavement management strategies and their alignment with the defined objectives. One of the evaluation metrics involves calculating the absolute difference in pavement conditions between underserved areas and other regions. This metric helps determine whether the optimization model successfully addressed the objective of minimizing disparities in pavement quality among different communities. By quantifying the absolute difference, the extent to which the pavement management strategies improved conditions in underserved areas compared to other areas can be assessed.

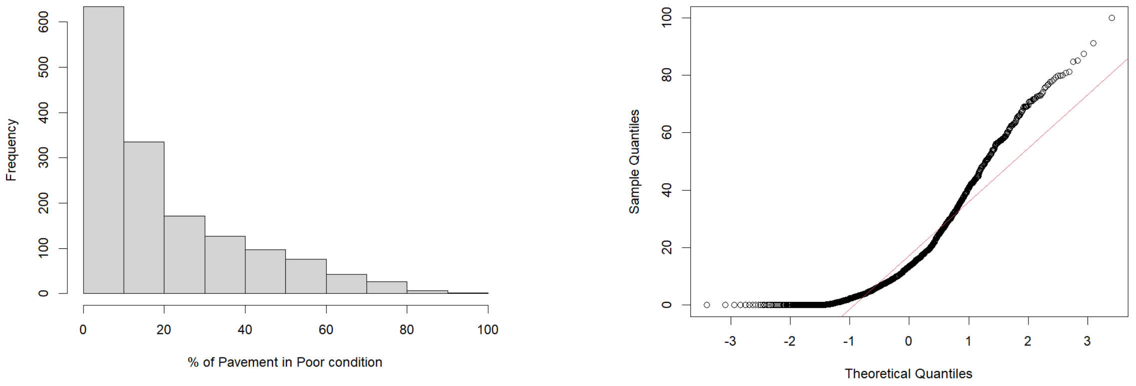
In addition, evaluating the total amount of GHG emissions associated with pavement management activities and traffic disruption is essential for assessing the environmental impact of the optimization model. By quantifying and minimizing these emissions, the transportation agency can make significant contributions to its environmental sustainability goals and reduce the carbon footprint of the pavement management program. Another critical evaluation metric is the average pavement condition. This metric serves as a reflection of the overall effectiveness of the optimization model in achieving its primary objective, which is to maximize the pavement condition. A higher average pavement condition indicates that the model successfully improved the overall quality of the road network.

2.5. Proposed Optimization Algorithm

The pseudocode in Appendix A (Algorithm A1) outlines the proposed framework for optimizing pavement management decisions. It defines three objective functions: minimizing disparity in pavement quality between underserved and other areas minimizing greenhouse gas emissions and maximizing overall pavement condition over a specific time period. Additionally, two constraints are enforced: staying within budget and ensuring all pavements meet a minimum acceptable condition after treatment. The code could generate all possible treatment plans, filter out those violating the constraints, evaluate the remaining plans based on the objectives, and select the optimal plan according to a user-defined selection process.

3. Results and Discussion

In the first step of the analysis, the Shapiro–Wilk test was conducted to investigate whether the dataset followed a normal distribution. The Shapiro–Wilk test is a hypothesis test designed to assess whether a dataset follows a normal distribution. This test examines data from a sample, operating under the null hypothesis that the dataset is normally distributed. A high *p*-value suggests that the dataset conforms to a normal distribution, whereas a low *p*-value indicates a departure from normal distribution. According to the results (Figure 3), the data did not follow a normal distribution. Therefore, non-parametric tests were employed for further analysis.



(**a**) Histogram

(**b**) Normal Q-Q plot

Figure 3. Histogram and normal QQ plot of pavement condition data.

As mentioned in the methodology, the dataset used in this study contains a wide range of potential factors, including age, educational level, poverty rate, race and ethnicity, population density, traffic, and air quality that could impact pavement condition. The Kruskal–Wallis test was utilized to analyze any significant relationships between the aforementioned factors and pavement conditions. This non-parametric test was selected due to the normality assumption of the dataset is violated. The Kruskal–Wallis test does not require data to be normally distributed, ensuring a more robust analysis. Results are presented in Table 3.

Table 3. Kruskal–Wallis test result.

	Poverty Rate	Air Quality	Traffic	Education Level	Race and Ethnicity	Population	Age
***p*-value**	0.001	0.0114	0.489	0.141	0.495	0.523	0.491

According to the results, the p-value for the poverty rate and air quality is less than 0.05, indicating a statistically significant relationship between these factors and pavement conditions. This suggests that the pavement condition may vary in areas with different rates of poverty and varying air quality. In other words, there is a significant difference in pavement conditions between areas with varying poverty rates and air quality levels. This highlights the importance for decision-makers to consider these factors in their management process to promote equity in their pavement management system.

However, factors such as population density, traffic, education, percentage of non-white population, and age, with p-values greater than 0.05, did not show a significant relationship with pavement condition in this specific dataset, which contradicts the findings in the Government Accountability Office (GAO) report [38]. This finding could be due to the fact that some agencies in the Bay Area have been considering race and ethnicity in their pavement management systems since 2017 [42]. However, further analysis needs to be conducted in individual areas to evaluate the effectiveness of that equity consideration. Currently, the Bay Area is being analyzed as a single data source. The results have also revealed a concerning observation regarding areas with higher poverty rates and areas with different ranges of air quality.

There are several machine learning methods for feature selection, with Lasso regression being one of the most common ones [9]. It can select useful features while discarding useless or redundant ones. In Lasso regression, discarding a feature will set its coefficient equal to 0. Therefore, in the next step, the Lasso regression method was applied to the dataset to achieve more precise results and determine the type of correlation, whether it is positive or negative. The results are shown in Table 4.

Table 4. Lasso regression method coefficient.

	Poverty Rate	**Air Quality**	**Traffic**	**Education Level**	**Race and Ethnicity**	**Population**	**Age**
Coefficient	0.10	0.27	0.00	0.00	0.00	0.0	0.01

According to the results, air quality showed a coefficient of 0.27, indicating a positive relationship with the percentage of pavement in poor condition. This suggests that areas with worse air quality correspond to a higher percentage of pavement in poor condition. Similarly, the poverty rate showed a coefficient of 0.1, supporting the observation that tracts with higher poverty rates tend to have a higher percentage of pavement in poor conditions. This implies that these two factors should be used as key indicators for defining underserved areas and should be incorporated as equity factors in the decision-making process. Decision-makers should consider these areas as underserved when allocating budgets or making decisions on M&R treatments if they want to establish an equitable management system.

On the other hand, the coefficients of other factors, such as race and ethnicity, educational level, population density, and traffic were aligned with the statistical results, showing coefficients of 0, indicating no significant relationship between these factors and pavement conditions in the dataset. The only contradictory finding was related to the factor of age. While the statistical analysis indicated that areas with a percentage of people older than 65 years had no correlation with pavement condition, the Lasso regression showed a slight increase in the percentage of pavement in poor condition, with a coefficient of 0.01.

This trend is further highlighted in Figures 4 and 5. Figure 4 demonstrates that tracts with higher poverty rates tend to have a greater percentage of pavement in poor conditions compared to areas with lower poverty rates. This indicates that these areas are more neglected or receive less attention for budget allocation for M&R projects, emphasizing the need for some equity adjustment in the decision-making process. Moreover, Figure 5 reveals that tracts with poor air quality mostly showed a higher percentage of pavement in poor condition compared to areas with better air quality. There are several possible explanations for these observations.

Figure 4. Pavement condition variation by poverty rate.

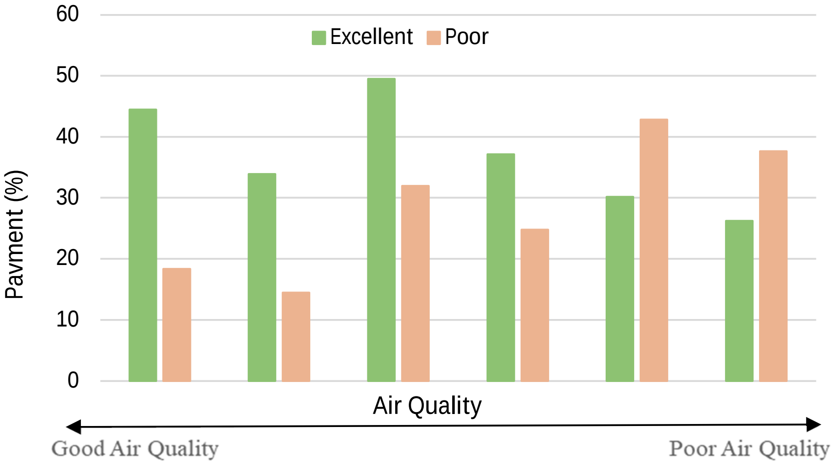


Figure 5. Pavement condition variation by air quality.

An important factor that could explain these findings is the land use type of the tracts, whether they are industrial or residential areas. Typically, air quality in industrial areas is lower compared to residential areas due to increased emissions and pollutants associated with industrial activities. Therefore, any potential relationship between the land use type and pavement condition should be investigated in future studies. Consequently, there is a possibility that the land use type should also be considered as another factor in defining underserved areas during the decision-making process. Additionally, the poor pavement condition itself could play a significant role in environmental issues. The presence of distressed pavement leads to frequent interruptions and traffic delays, which result in increased fuel consumption, higher emissions, and carbon footprint, which is one of the most important contributing factors in environmental equity assessments.

In conclusion, both the statistical analysis and Lasso regression results highlight air quality and poverty rate as the most influential factors for defining underserved areas, which might be considered in an equitable pavement management planning. The statistical analysis revealed that these factors have p-values less than 0.05, signifying their statistical significance. Moreover, the Lasso regression revealed non-zero coefficients, further supporting their importance in the decision-making process.

4. Potential Limitation and Biases

When proposing a framework that integrates social equity, environmental equity, and economic considerations into pavement management systems, it is crucial to recognize several significant limitations and potential biases. Firstly, the availability and quality of data related to social, environmental, and economic factors may vary across regions, potentially constraining the framework's generalizability. This introduces a possible bias, where regions with more robust data collection infrastructure might be overrepresented in assessing the framework's effectiveness.

Another critical consideration involves the inherently subjective nature of assessing social and environmental equity. Divergent views among stakeholders on what constitutes equitable outcomes can introduce biases in decision-making. Additionally, economic conditions are dynamic, and the framework's reliance on economic factors may face challenges in adapting to changing circumstances. Economic biases may emerge if the framework lacks flexibility to accommodate variations in economic conditions.

Furthermore, the framework may not fully account for cultural and regional differences, posing limitations in its applicability in diverse contexts and potentially introducing cultural biases. Temporal dynamics also pose a challenge, as the framework may not adequately address long-term changes in social, environmental, or economic factors, limiting its relevance over time.

The effectiveness of the framework may also depend on stakeholder engagement, and challenges in obtaining meaningful participation could hinder successful implementation, potentially introducing biases in decision-making processes, especially if certain perspectives are underrepresented. Addressing these limitations through careful consideration, sensitivity analyses, and transparent decision-making processes is crucial for ensuring the robustness and applicability of the proposed framework in pavement management systems.

Finally, it is important to note the potential for endogeneity in these types of analyses. Endogeneity can arise when there is a bidirectional relationship between the variables considered, meaning that the causal relationship may not be straightforward. In situations where endogeneity is present, the framework's ability to disentangle and accurately model the causal relationships may be compromised. This could impact the effectiveness of the decision-support system, as interdependencies among variables may introduce biases in the allocation of budgets. For example, improving the conditions in an underserved area may lead to changes in the social, economic, and environmental factors, influencing the overall dynamics of the pavement management system.

To address the endogeneity concerns, advanced statistical techniques like instrumental variables (IV) or control function methods could be employed in. These techniques aim to extract the exogenous component of the endogenous variables, breaking the correlation between the endogenous variables and the error term. Additionally, sensitivity analyses using methods like the Hausman test or two-stage least squares (2SLS) can be conducted to check for the presence of endogeneity and assess the robustness of the results. By employing these advanced statistical techniques and sensitivity analyses, the framework's ability to accurately model the causal relationships can be enhanced, mitigating potential biases introduced by endogeneity in the allocation of budgets.

5. Conclusions

In the world of infrastructure development, asset management in a sustainable manner could affect people in different communities, environments, and economic growth. However, achieving sustainable asset management has many challenges when trying to balance economic, environmental, and social equity objectives.

Balancing the economic, environmental, and social aspects of pavement management involves making careful choices. On the economic front, efforts to enhance social and environmental equity may necessitate significant initial financial investments. For instance, initiatives like constructing new roads in underserved areas or electrifying vehicle fleets to mitigate environmental impact can strain already limited transportation budgets due to high upfront infrastructure and operating costs.

However, certain pavement management strategies demonstrate that economic goals need not always conflict with environmental and social equity objectives. These approaches often yield both environmental and social benefits at lower financial costs.

Policies solely focused on social equity in pavement management may result in overall efficiency losses, potentially leading to greater environmental impacts, higher user costs, and strained budgets for agencies. Nevertheless, well-designed investments targeting traditionally underserved groups have the potential to unlock productivity gains and catalyze economic growth.

This research aimed to develop a prototype decision-support framework for allocating budgets in transportation asset management projects, covering all three equity aspects simultaneously. The focus was on pavement maintenance, rehabilitation, and reconstruction projects. The framework proposed in this study consists of three steps. The first step was defining the research objective, followed by some analysis to investigate key factors in defining underserved areas based on a case study dataset, and then developing an optimization model and finalizing by evaluating the model with some metrics. The optimization model aims to minimize the assets' condition gap between underserved areas and the rest of the network, minimize greenhouse gas emissions, and maximize road network conditions.

The case study was a comprehensive dataset for California's Bay Area, containing sociodemographic and local pavement condition data. The analysis of this dataset revealed that areas with different poverty rates and air quality experience varying pavement conditions. Areas with higher poverty rates and worse air quality tend to have a higher percentage of pavement in poor condition. The Lasso regression method also provided more precise results, confirming the positive correlation between poor air quality and higher poverty rate with the percentage of pavement in poor condition. Furthermore, it revealed a slight increase in poor pavement conditions in areas with an older population. These results highlight that these factors should be considered in the decision-making process to establish an equitable pavement management system.

The findings indicate that land use type might also be an important factor to consider in decision-making process conditions and should be investigated in further studies. Moreover, it shows that poor pavement condition itself might contribute to environmental issues by causing traffic disruptions, increased fuel consumption, and higher emissions, influencing environmental equity assessments. In conclusion, this study's integrated decision-support framework offers valuable insights for sustainable pavement management.

It should be noted that the correlation between poor pavement conditions and impoverished socioeconomic conditions, as observed in the reviewed data, may not universally apply. Factors such as geographical location, economic development, and cultural influences could potentially modify the relationship between pavement conditions and socioeconomic conditions. Despite these considerations, the described framework appears robust and suitable for dissemination to other regions with available data. Considering economic, environmental, and social equity factors simultaneously allows for more informed budget allocation decisions, promoting equitable development and enhancing transportation infrastructure. Future studies can explore additional factors and land use characteristics to refine the framework and further enhance its application in real-world scenarios.

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Appendix A

Algorithm A1. Proposed multi-objective pavement management algorithm (pseudocode).

```
#Define objective functions
function objective_1(pavement_conditions)
    underserved_condition ← average_condition (pavement_conditions, is_underserved=True)
    other_condition ← average_condition (pavement_conditions, is_underserved=False)
    return |underserved_condition—other_condition|
end function
function objective_2(treatment_plan)
    construction_emissions ← sum (treatment.construction for treatment in treatment_plan)
    traffic_emissions ← sum (treatment.traffic for treatment in treatment_plan)
    return construction_emissions + traffic_emissions
end function
function objective_3(treatment_plan, time_period)
    total_condition ← sum(section.condition_after_treatment(treatment) for section, treatment in zip(pavement_sections, treatment_plan))
    return total_condition/time_period
end function
#Define constraints
function budget_constraint(treatment_plan)
    total_cost ← sum(treatment.agency_cost for treatment in treatment_plan)
    return total_cost ≤ available_budget
end function
function performance_constraint(treatment_plan)
    for each section, treatment in zip(pavement_sections, treatment_plan) do
        if section.condition_after_treatment(treatment) < minimum_acceptable_condition then
            return False
        end if
    end for
    return True
end function
#Define the multi-objective optimization problem
function optimize_pavement_management(pavement_sections, available_budget, time_period)
    all_treatment_plans ← generate_all_treatment_plans(pavement_sections)
    feasible_plans ← []
    for each plan in all_treatment_plans do
        if budget_constraint(plan) and performance_constraint(plan) then
            feasible_plans.append(plan)
        end if
    end for
    objectives ← []
    for each plan in feasible_plans do
        obj1 ← objective_1(plan)
        obj2 ← objective_2(plan)
        obj3 ← objective_3(plan, time_period)
        objectives.append((obj1, obj2, obj3))
    end for
    optimal_plan ← select_optimal_plan(objectives)
    return optimal_plan
end function
```

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