Project 2330 | June 2024

SJSU SAN JOSÉ STATE UNIVERSITY

MINETA TRANSPORTATION INSTITUTE

Examining Transit Service Improvements with Internet-of-Things (IoT): A Disparity Analysis

Shailesh Chandra, PhD Robert Valencia Vamsi Krishna Oruganti

CSUTC California State University Transportation Consortium

CALIFORNIA STATE UNIVERSITY LONG BEACH

MINETA TRANSPORTATION INSTITUTE

Founded in 1991, the Mineta Transportation Institute (MTI), an organized research and training unit in partnership with the Lucas College and Graduate School of Business at San José State University (SJSU), increases mobility for all by improving the safety, efficiency, accessibility, and convenience of our nation's transportation system. Through research, education, workforce development, and technology transfer, we help create a connected world. MTI leads the Mineta Consortium for Transportation Mobility (MCTM) and the Mineta Consortium for Equitable, Efficient, and Sustainable Transportation (MCEEST) funded by the U.S. Department of Transportation, the California State University Transportation Consortium (CSUTC) funded by the State of California through Senate Bill 1 and the Climate Change and Extreme Events Training and Research (CCEETR) Program funded by the Federal Railroad Administration. MTI focuses on three primary responsibilities:

Research

MTI conducts multi-disciplinary research focused on surface transportation that contributes to effective decision making. Research areas include: active transportation; planning and policy; security and counterterrorism; sustainable transportation and land use; transit and passenger rail; transportation engineering; transportation finance; transportation technology; and workforce and labor. MTI research publications undergo expert peer review to ensure the quality of the research.

Education and Workforce Development

To ensure the efficient movement of people and products, we must prepare a new cohort of transportation professionals who are ready to lead a more diverse, inclusive, and equitable transportation industry. To help achieve this, MTI sponsors a suite of workforce development and education opportunities. The Institute supports educational programs offered by the Lucas Graduate School of Business: a Master of Science in Transportation Management, plus graduate certificates that include High-Speed and Intercity Rail Management and Transportation Security Management. These flexible programs offer live online classes so that working transportation professionals can pursue an advanced degree regardless of their location.

Information and Technology Transfer

MTI utilizes a diverse array of dissemination methods and media to ensure research results reach those responsible for managing change. These methods include publication, seminars, workshops, websites, social media, webinars, and other technology transfer mechanisms. Additionally, MTI promotes the availability of completed research to professional organizations and works to integrate the research findings into the graduate education program. MTI's extensive collection of transportation-related publications is integrated into San José State University's world-class Martin Luther King, Jr. Library.

Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and accuracy of the information presented herein. This document is disseminated in the interest of information exchange. MTI's research is funded, partially or entirely, by grants from the U.S. Department of Transportation, the U.S. Department of Homeland Security, the California Department of Transportation, and the California State University Office of the Chancellor, whom assume no liability for the contents or use thereof. This report does not constitute a standard specification, design standard, or regulation.

Report 24-13

Examining Transit Service Improvements with Internet-of-Things (IoT): A Disparity Analysis

Shailesh Chandra, PhD

Robert Valencia

Vamsi Krishna Oruganti

June 2024

A publication of the
Mineta Transportation Institute
Created by Congress in 1991

College of Business
San José State University
San José, CA 95192-0219

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. 24-13	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Examining Transit Service Improvements with Internet-of-Things (IoT): A Disparity Analysis		5. Report Date June 2024
		6. Performing Organization Code
7. Authors Shailesh Chandra, PhD Robert Valencia Vamsi Krishna Oruganti		8. Performing Organization Report CA-MTI-2330
9. Performing Organization Name and Address Mineta Transportation Institute College of Business San José State University San José, CA 95192-0219		10. Work Unit No.
		11. Contract or Grant No. ZSB12017-SJAUX
12. Sponsoring Agency Name and Address State of California SB1 2017/2018 Trustees of the California State University Sponsored Programs Administration 401 Golden Shore, 5th Floor Long Beach, CA 90802		13. Type of Report and Period Covered
		14. Sponsoring Agency Code
15. Supplemental Notes 10.31979/mti.2024.2330		

16. Abstract

Literature shows that poor service reliability of transit often leads to uncertain waiting times at transit stations, diminishing their popularity and usage, and this particularly affects low-income populations more likely to rely heavily on transit. This research delves into an in-depth analysis of the inequality assessment of the Los Angeles (LA) Metro Rail lines, with a particular focus on evaluating the potential impacts of integrating Internet of Things (IoT) technology. This study investigates how IoT could influence service connectivity, accessibility, and the existing disparities in transit services. The primary goal of this study is to assess how the implementation of IoT technology could enhance the connectivity and accessibility of LA Metro Rail services, and whether such technological advancements could contribute to mitigating service inequality. The research methodology encompasses a comprehensive analysis of connectivity and accessibility values across all LA Metro Rail lines for the years 2015, 2017, and 2019. This approach allows for evaluating the potential impact of IoT technology on service connectivity and accessibility for inequality. The study considers several factors, including potential ridership based on low-income populations' proximity to transit stations and the integration process of IoT technologies within the rail service infrastructure. The study reveals that IoT implementation could significantly improve service accessibility across all rail lines, indicating a positive trend in technological advancements enhancing public transit. However, the impact on reducing service inequality is inconsistent. Notably, Rail Line B would experience fluctuating accessibility with IoT, while Rail Line C showed persistent inequality under IoT deployment scenarios. These findings suggest that while IoT could hold promise for enhancing service quality, its effectiveness is subject to a range of influencing factors, scheduled frequency and stops at stations for the transit rail lines as well as the presence of low-income populations near these stations.

17. Key Words Transit, Inequality, Performance, Connectivity, Accessibility	18. Distribution Statement No restrictions. This document is available to the public through The National Technical Information Service, Springfield, VA 22161.		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 31	22. Price

Form DOT F 1700.7 (8-72)

Copyright © 2024

by **Mineta Transportation Institute**

All rights reserved.

DOI: 10.31979/mti.2024.2330

Mineta Transportation Institute
College of Business
San José State University
San José, CA 95192-0219

Tel: (408) 924-7560
Fax: (408) 924-7565
Email: mineta-institute@sjsu.edu

transweb.sjsu.edu/research/2330

Acknowledgments

The research team would like to thank MTI for the funding received to conduct this research.

CONTENTS

Acknowledgments.....vi

List of Figures.....viii

List of Tables.....ix

Executive Summary.....1

1. Introduction and Background.....2

2. Methodology.....6

    2.1 Connectivity.....6

    2.2 Accessibility.....6

    2.3 Generalized Connectivity-accessibility Index.....7

    2.4 Inequality Measurement.....7

    2.5 Performance persistence analysis.....8

3. Analysis and Results.....10

4. Summary & Conclusions.....16

Bibliography.....17

About the Authors.....21

LIST OF FIGURES

Figure 1. Spatial Distribution of Low-Income Workers Residence Along LA Metro 5

Figure 2. Accessibility of LA Metro Rail Lines '*without*' IoT Considering Ridership from Low-Income Population 11

Figure 3. Accessibility of LA Metro Rail Lines 'with' IoT Considering Ridership from Low-Income Population 11

Figure 4. Inequality Values Using Accessibility of The Rail Line 'without' IoT....................12

Figure 5. Inequality Values Using Accessibility of The Rail Line 'with' IoT.........................13

List of Tables

Table 1. Data Used for Analysis 10

Table 2. Differences in Inequality Values (scenario 'without' IoT minus 'with' IoT) for Rail Line for Years 2015, 2017, and 2019..14

Table 3. Potential Winners (+ve value in Table 2) and Losers (-ve value in Table 2)................15

Executive Summary

This study provides an evaluation of the potential impacts of Internet of Things (IoT) technology on the Los Angeles (LA) Metro Rail lines, focusing on service connectivity, accessibility, and the implications for inequality among transit services. It highlights the critical role of reliable, timely information for passengers, especially those from low-income populations who rely heavily on public transit and are most affected by service inconsistencies.

The IoT technology, if implemented, is shown to potentially increase accessibility across all LA Metro Rail lines (A, B, C, D, and E) for the years studied (2015, 2017, and 2019). This suggests that technological advancements could significantly enhance service accessibility, making public transit more efficient and accessible.

Despite the overall improvements in accessibility, the effects of IoT on reducing service inequality are inconsistent. Rail Line B experienced fluctuating accessibility values with IoT implementation, while Rail Line C showed persistent inequality. This indicates that while IoT can improve service quality, its effectiveness varies due to factors such as potential ridership and the integration process of IoT technologies.

The research underscores the complexities involved in deploying technology within public infrastructure. The persistence of inequality in service levels, even with IoT adoption, suggests that a planned approach is necessary for implementing technological solutions.

The study suggests that technology alone may not be sufficient to address systemic issues within public transit systems. Infrastructure readiness, the socioeconomic status of users, and strategic technology integration must be considered to achieve more equitable outcomes.

The research calls for further exploration of the conditions under which IoT technologies can most effectively reduce service inequality. It is recommended that longitudinal studies could provide insights into the sustainability of improvements in accessibility and service quality over time. Comparative studies across different transit systems could identify best practices for IoT integration.

There is a need to develop inclusive strategies that consider the diverse needs of all transit users, especially marginalized communities, to ensure equitable access to improved services. This involves technological upgrades, infrastructural improvements, policy interventions, and community engagement efforts to address broader issues of inequality in urban mobility.

In conclusion, while IoT has the potential significantly to improve public transit by enhancing accessibility and connectivity, the uneven benefits observed across different rail lines highlight the need for careful consideration of factors to ensure that technology deployment contributes to more equitable outcomes in public transit systems.

1. Introduction and Background

Literature shows that poor service reliability of transit often leads to uncertain waiting times at transit stations, diminishing their overall popularity and usage (Perk et al., 2008). The popularity of transit is often negatively impacted by poor infrastructure of other modes that also provide first/last mile connectivity to a transit system (Chandra et al., 2016). In addition, failure to provide timely information to passengers on service disruptions is also perceived as a disincentive for transit use (Watkins et al., 2011).

Commuters from low-income populations who do not own private vehicles often rely heavily on transit. They are the most affected by a lack of information on accurate arrival and departure times of transit at a stop. For example, in the Southern California Region, the light rail lines of the LA Metro offer commuter service to passengers who are primarily from low-income populations. These rail lines include A Line, B Line, C Line, D Line, and E Line (see the map in Fig. 1 for low-income population residing around the half-mile area around each line). These light rail transit lines connect to Los Angeles Union Station, which is also a proposed California high-speed rail station (LA Union Station, 2018). However, despite serving a dense urban population, the rail lines have been experiencing a low ridership compared to those for other transit systems in other states such as New York. Data from the last seven years show a systemwide ridership decrease of almost 20% for the rail lines before the COVID-19 pandemic during the previous five years and experienced even further reductions in ridership after the pandemic in the last two years (LA Metro 2022). Therefore, there is a need to address the low ridership that most transit systems in California (and elsewhere in the United States) are experiencing.

To improve ridership, transit must be attractive and seamlessly useful for its riders through technology usage. For example, the Internet-of-Things (IoT) is one such innovative technology that ensures the fast and efficient relay of information to passengers on accurate arrival/departure times of rail at stations (Patel et al., 2019). This is achieved through interconnected transportation entities, such as train locations, commuters (mobile phones), sensors installed at stations, and seamless connectivity between passengers and rail (Chavhan et al., 2019). Studies show that technologies and smartphone applications that help improve the reliability of the information on transit locations are on the rise (Misra et al., 2014), especially in the smart city applications with connectivity and accessibility provided by smart trains (Fraga-Lamas et al., 2017; Zhao et al., 2020; Kyriazis et al., 2013).

IoT is a network of interconnected, uniquely identifiable devices, such as a mobile phone, which exhibits communications capable of being used and embedded at any scale within the transportation system (USDOT 2016). With IoT-based Intelligent Public Transportation Systems (IoT-IPTS), service reliability and heterogeneity among connected objects or modes are improved for a multimodal transport system, enhancing connectivity and accessibility to stations.

Waiting at stations or stops is often perceived as a deterrent to riding transit (Taylor et al., 2009), and it can thus be eliminated with IoT-IPTS to help transit agencies attract the much-needed ridership. However, the question arises of how well all these enhancements affect the equity goals of a transit agency that facilitates travel for low-income commuters.

The primary purpose of improving rail service (through technology deployments) is to attract ridership (Chandra and Mazin, 2020). Investments through new technology implementation in transit are justified if improvements are observed in two popular transit performance measures—connectivity and accessibility (Chandra et al., 2018). Connectivity conveys how well two places are connected, whether from improvements in transportation infrastructure or from service improvements between regions, cities, or points of interest; and accessibility is expressed as travel time, distance, or cost requirements to access a destination (Karou and Hull, 2014). However, these two measures rarely have been evaluated when incorporating IoT benefits—particularly for equity assessments for connected and accessible transit for low-income riders.

Low-income populations have been a focus of various equity-related studies, emphasizing the impacts of transport connectivity and accessibility (Bröcker et al., 2010). In one study, scholars found that accessibility increased among low-wage workers compared to medium and high-wage workers after implementing the light rail line service (Fan et al., 2012). In all the connectivity and accessibility-related findings, assessing inequality impacts can be a challenge—but for this, suggestions have been made to use spatial impact analysis derived from changes to the distribution of accessibility in the specific urban agglomerations of rail projects (Monzón et al., 2013). Thus, the presence of rail stations, proximity to population centers, and the quality of the overall transportation system impact the inequality implications. With the deployment of innovative technologies such as IoT-IPTS and measuring the resulting connectivity and accessibility of transit, the usefulness of such technologies can be better understood to make policy decisions that meet the equity goals of transit agencies.

Light rail transit is often seen to play an essential role in attenuating regional inequalities between places that are far apart—mainly by providing transport solutions to commuters from poor and disadvantaged communities (Wu et al., 2020). Light rail can potentially address accessibility concerns for underprivileged communities (Constantin et al., 2021). However, this may not always be true, and realizing any benefits through IoT-IPTS deployment in enhancing connectivity or accessibility could be complex or even contrary to expectations. For example, past studies have shown that an increase in disparities can also result from an increase in infrastructure connectivity—when the more prominent locations draw increased resources from the other locations (Fujita and Thisse, 1996). This entails studying rail connectivity and accessibility impacts on inequality with IoT-IPTS implementation, especially for stations and rail lines that serve low-income commuters.

To measure the inequalities by rail, three commonly used measures can be deployed, and these include dispersion indices such as coefficient of variation (Gutiérrez, 2001), Gini coefficient based on Lorenz curve [25], and entropy index such as the Thiel's index [24]. While measuring inequality, it is important to consider how attractive a rail transport system is for a broad societal range and whether it can maintain a sustained level of ridership. This is especially needed in nations like the USA where rail ridership has been particularly low post COVID-19 [26].

This research proposes new connectivity and accessibility measures for passenger rail transportation, considering the impacts of IoT-IPTS. Subsequently, a customized inequality formulation will be developed to imbibe the two measures. Analysis of these measures will be conducted with the light rail lines of LA Metro used as an example. Further, a performance persistence analysis (PPA) will be conducted using 'with' and 'without' IoT-IPTS implementation for the light rail lines. PPA has been used in a variety of transit-related studies [27]. It will identify winners and losers of rail lines, indicating if LA Metro needs to increase its frequency of service to any specific rail line to meet equitable connectivity and accessibility goals to serve low-income riders.

Knowing winners and losers will help planners and policy-makers channel appropriate capital investments to rail lines of LA Metro and increase its connectivity and/or accessibility to minimize their disparities. Compared to all the past research, our methodology is unique as it will deploy socioeconomic data, station-level connectivity and accessibility of the rail lines incorporating IoT-IPTS to deduce percentage changes in inequality. This approach encompasses sensitivity both from the disparity and performance measures perspectives of rail transit.

Further, the methodology developed in this research can be adopted by any transit system incorporating IoT in their operations.

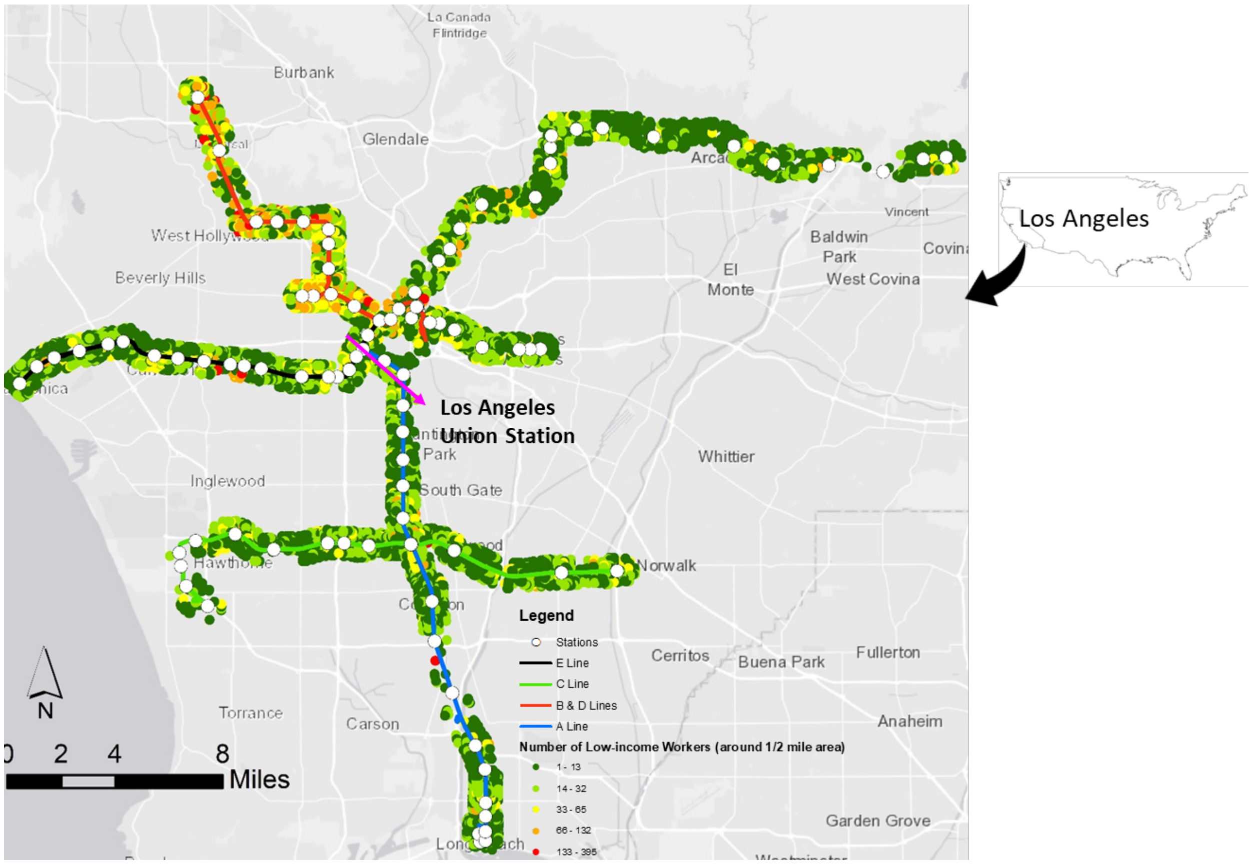

Figure 1. Spatial Distribution of Low-Income Workers Residence Along LA Metro

2. Methodology

We begin by adapting a conventional formulation for connectivity and accessibility, incorporating them into the inequality formulation. Centrality, a key topological feature in network analysis, is employed for the connectivity aspect, a concept extensively utilized in various fields like physical networks, computer science, and epidemiology (Mishra et al., 2012). While connectivity captures a network's topological characteristics, accessibility serves as another frequently employed metric for assessing passenger flow (Liu et al., 2020).

Using the two measures of connectivity and accessibility, the topology and the passenger flow were simultaneously considered (Sun et al., 2018). Though various forms of these two measures exist in the literature, none we came across was sensitive to the train's scheduled arrival or departure times within a network. Therefore, both connectivity and accessibility measures were developed to be time-sensitive and reflect trains' schedule effects. Some of the key methodological steps discussed in the next sections have been adopted from Chandra and Narayanaswami (2024).

2.1 Connectivity

The "degree centrality" formula has been modified to develop the connectivity measure. The degree centrality of a node is the number of edges it has (Golbeck, 2013). It is usually deployed to identify the most important node in a network and indicates the number of neighboring stations directly next to a station (Chen et al., 2022). This means that the higher the centrality of the node, the more central and connected it is to the other nodes. In the formulation for centrality presented here, we use the centrality measure as a station's connectivity.

The connectivity formula (denoted using $C_{i,z}^{y}$) for a node or a station i on transit line l in the year y is expressed as:

$$C_{i,l}^{y} = \sum_{j=1}^{J_l} \left(\frac{1}{I_{i,j}^{y}} \right) \tag{1}$$

where, $I_{i,j}^{y}$ is the impedance in the year y between station i and closest station j (with $i \neq j$), and J_l is the number of neighboring stations in the transit line l.

2.2 Accessibility

Accessibility derived from a transportation facility (such as rail) is often used as a surrogate for a region's economic potential and attractiveness (Chandra and Vadali, 2014). With a focus on the accessibility (or attraction) of a station on a transit line, a formula is proposed for its accessibility, $A_{i,l}^{y}$, for a station i on the line l in the year y and is expressed as:

$$A_{i,l}^{y} = \sum_{j=1}^{J_l} \frac{P_j^y}{I_{i,j}^y} \tag{2}$$

where, P_j^y is the low-income population (as potential ridership) around the station *j* in the year *y*, $I_{i,j}^y$ is the impedance in the year *y* between station *i* and a closest station *j* (with $i \neq j$), and J_l is the number of neighboring stations on the transit line *l*. The impedance is determined for the 'with' and 'without' IoT deployment cases. For the 'without' IoT case, the impedance consists of the sum of the waiting time and the travel time to the next station on the same line. The waiting time is zero in the impedance calculated for the 'with' IoT case.

2.3 Generalized Connectivity-accessibility Index

For a rail passenger, although a station with the largest connectivity would be attractive, there is a possibility that this may not be true when travel times from one station to the other stations are high—since connectivity expressed in Eq. (1) does not take into consideration the travel time between stations. Alternatively, accessibility—involving station/city population and travel times between stations—presents a more holistic measure of the attractiveness for rail passengers (Chandra and Vadali, 2014).

As evident from this research, both connectivity and accessibility are equally important for enjoying the benefits of rail transportation (Zhou et al., 2018). To account for both centrality (i.e., connectivity) and accessibility measures, we develop a generalized measure ($\Omega_{i,z}^y$) for a station *i* line *l* for the year *y* expressed as:

$$\Omega_{i,z}^{y} = \begin{cases} C_{i,l}^{y} \text{ if connectivity is sought} \\ A_{i,l}^{y} \text{ if accessibility is sought} \end{cases} \tag{3}$$

Therefore, the generalized connectivity and accessibility index, Ω_l^y, for a line (with stations) is the average of $\Omega_{i,l}^y$ of all the stations contained in that zone.

2.4 Inequality Measurement

The inequality is measured for a transit line based on the connectivity and accessibility of all the stations on the line. Analyzing inequality or disparity among lines at the spatial scale can reveal gaps in transit connectivity and accessibility which can further justify and guide future transit-level investments. Thus, historically, lines with stations that may or may not have benefitted from IoT deployment are identified with the disparity analysis. A disparity analysis can reflect any modifications, expansions, or adjustments in schedule needed in operating transit service with IoT, to provide a more efficient connectivity and accessibility to the low-income population.

In this paper, we use a modified form of entropy index (Theil's T index) as a decomposable measure of inequality that can be disintegrated into population groups, income sources, or other dimensions (Theil, 1967; Cowell, 2006).

The modified Theil T index (T_l^y), representing inequality, for a transit line *l* in year *y* incorporating the generalized connectivity-accessibility index of a station is expressed as:

$$T_l^y = \frac{1}{n_l} \sum_{i=1}^{n_l} \frac{\Omega_{i,l}^y}{\bar{\Omega}_l^y} \ln\left(\frac{\Omega_{i,l}^y}{\bar{\Omega}_l^y}\right) \tag{4}$$

where,

n_l= number of stations on a transit line *l* (assumption is that the total number of stations remains constant during each analyzed year *y*)

$\Omega_{i,l}^y$= measure of the connectivity or accessibility of station *i* on line *l* in year *y*

$\bar{\Omega}_l^y$= mean connectivity or accessibility for all the stations on line *l* in year *y*.

Henceforth, we utilize the inequality formulation above to evaluate the performance of transit lines for connectivity and accessibility, as described in the next section.

2.5 Performance persistence analysis

A nonparametric method is utilized to assess the performance of a transit line both 'with' and 'without' IoT deployment. The aim is to analyze connectivity and accessibility. The performance analysis guides stakeholders to achieve regional and social inequality by directing investments in public transport (Zhao and Li, 2019; Luo and Zhao, 2021; Kim and Yi, 2019).

Transit-level performance analysis should be conducted to understand how lines might have improved in inequality over the years, if IoT was deployed. Therefore, we classify lines into winners and losers based on their performance, assessed through inequality improvement 'with' or 'without' IoT deployment. A similar performance assessment has been adopted by Zhou et al. (2018) for rail transit.

Utilizing the fundamentals of the theory of performance persistence analysis (PPA) by Agarwal and Naik (2000), the formulation for the percentage change in inequality between 'with' and 'without' IoT for a transit line is developed to determine the winning and losing lines. The inequality used here can be derived interchangeably from connectivity or accessibility using Eq. (3) and (4).

The percentage change in inequality (E_l^y) is expressed as,

$$E_l^y = \frac{T_l^{wo,y} - T_z^{w,y}}{T_l^{wo,y-1}} \tag{5}$$

where,

$T_l^{wo,y}$ is the inequality for the 'without' IoT case for year *y*, and

$T_l^{w,y}$ is the inequality for the 'with' IoT case for year *y*.

A winning transit line is decided if $E_l^y > 0$, otherwise the line is classified as a losing line. Furthermore, a cross-product ratio is evaluated to indicate the odds ratio of the number of repeat performers (i.e., win–win and lose–lose) to the number of others (i.e., win–lose and lose–win) for the two cases considered across two consecutive years.

Once the winner/loser zones are determined, the cross-product ratio is computed using the odds ratio of the number of repeat performers, whether winners or losers, in two consecutive years. The formula for the odds ratio, $O_{y-1,y}$, is expressed as:

$$O_{y-1,y} = \left(\frac{WW_{y-1,y} \times LL_{y-1,y}}{WL_{y-1,y} \times LW_{y-1,y}}\right) \tag{6}$$

where,

$WW_{y-1,y}$= number of lines that are categorized as winners for two consecutive analysis periods/years (*y-1* and *y*),

$LL_{y-1,y}$= number of lines that are categorized as losers for two consecutive analysis periods/years (*y-1* and *y*),

$WL_{y-1,y}$= number of lines that are categorized as winners in the analysis period/year *y*-1 and losers in the analysis period/year *y*, and

$LW_{y-1,y}$= number of lines that are categorized as losers in the analysis period/year *y*-1 and winners in the analysis period/year *y*.

The odds ratio in Eq. 6, if above 1, indicates a positive association between an outcome (e.g., being a winner or loser) in one time period/year and the same outcome in the subsequent period/year. Alternatively, the odds ratio, if less than 1, indicates a negative association, which means that the outcome in the following period is more likely to be the opposite of the outcome in the previous period.

3. Analysis and Results

The results presented in the tables provide a comparison of accessibility values for rail lines 'with' and 'without' the implementation of Internet of Things (IoT) technology, as well as the corresponding inequality values derived from these accessibility metrics. Data for the years 2015, 2017 and 2019 are used for demonstration and analysis with LA Metro rail lines: A-E. Data sources for the analysis are shown in Table 1. Low-income populations are those with household income less than $1,250 per month.

Table 1. Data Used for Analysis

Data Type	Sources	Input for?
Schedule/Travel time (A Line, B Line, C Line, D Line, and E Line)	LA Metro Maps and Schedules*	Connectivity Measure Accessibility Measure
Low-income Employment Data and Distance traveled	Center of Economic Studies, Longitudinal Employer-Household Dynamics (LEHD), 2019.	Accessibility Measure Inequality Measure
Transit Lines, Stops and Stations	GIS Data LA Metro**	Connectivity and Accessibility Measures

* https://www.metro.net/riding/schedules/
** https://developer.metro.net/gis-data/

The charts in Fig. 2 and Fig. 3 show the accessibility values for rail lines without and with IoT, respectively. Higher accessibility values indicate better service or performance. Comparing the two tables, it is evident that IoT implementation has resulted in higher accessibility values across all rail lines and years. For instance, Rail Line A shows an increase from 374 to 969 in 2015 with IoT, suggesting a significant improvement in accessibility due to IoT.

Similar trends can be observed in other rail lines, although Rail Line B shows a marked decrease in accessibility from 2015 to 2019 even with IoT, indicating that other factors may have affected its performance.

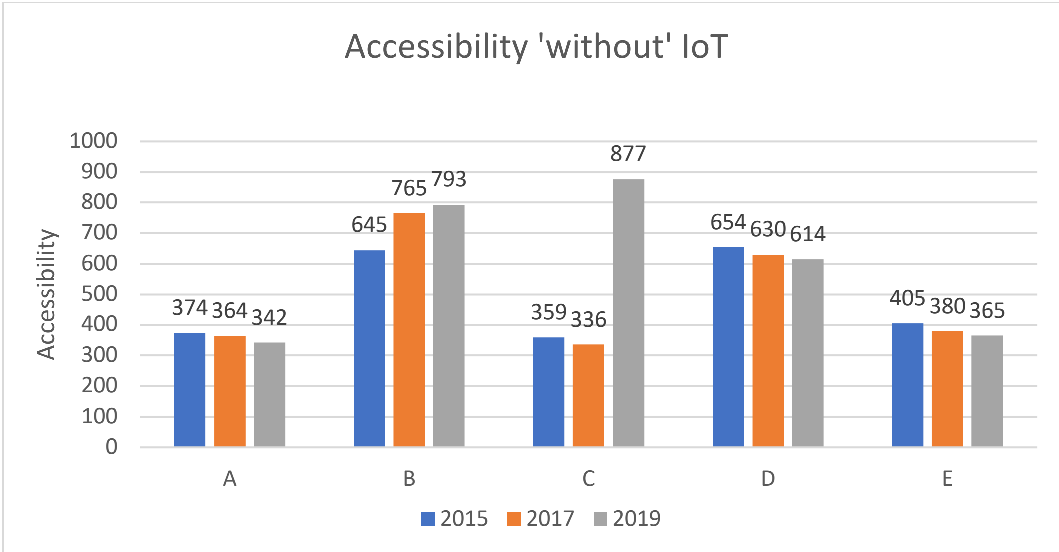

Figure 2. Accessibility of LA Metro Rail Lines '*without*' IoT Considering Ridership from Low-Income Population

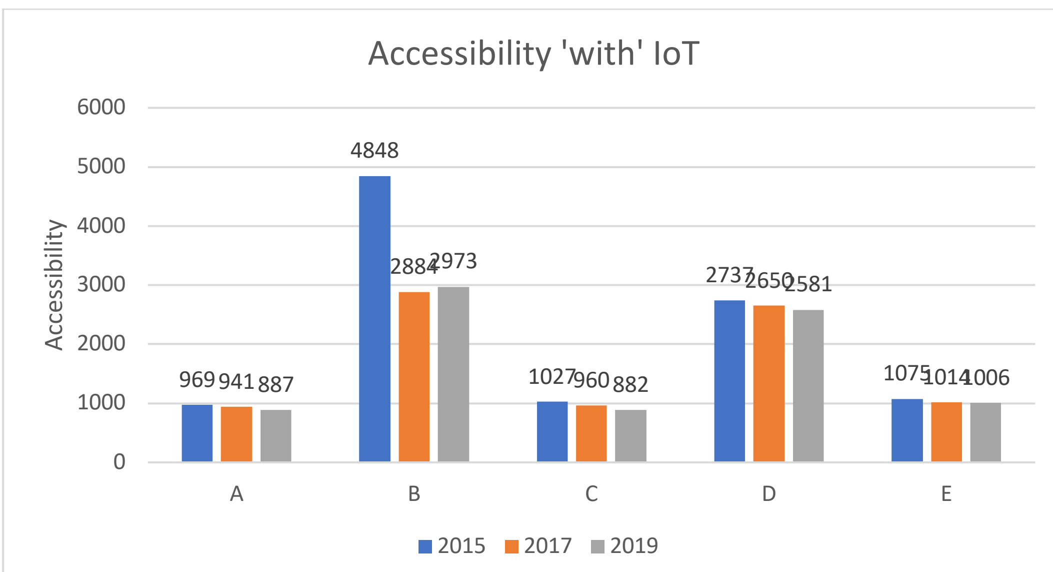

Figure 3. Accessibility of LA Metro Rail Lines 'with' IoT Considering Ridership from Low-Income Population

The charts in Fig. 4 and Fig. 5 present the inequality values calculated using the accessibility of the rail lines without and with IoT, respectively. These values represent the disparity in service levels, with lower values indicating more uniform service across the network. Notably, Rail Line C has the highest inequality values without IoT, which decrease marginally with IoT. This suggests that while IoT has improved overall accessibility for Rail Line C, it has not significantly affected the service disparity. Conversely, Rail Line B sees a reduction in inequality from 0.17 in 2015 without IoT to 0.11 with IoT, indicating that IoT implementation has contributed to a more equitable service.

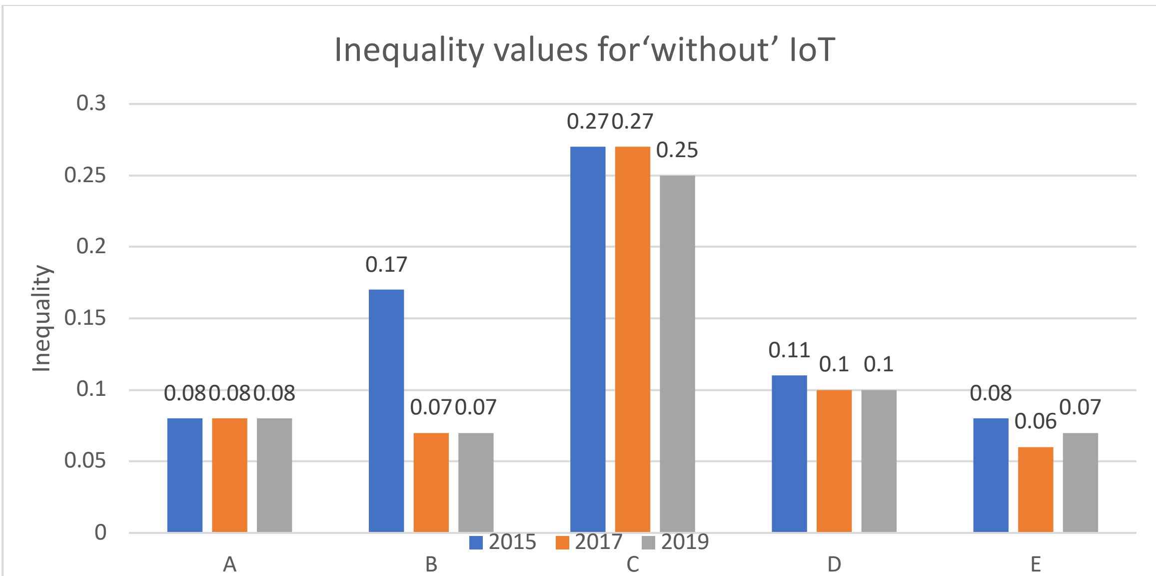

Figure 4. Inequality Values Using Accessibility of The Rail Line 'without' IoT

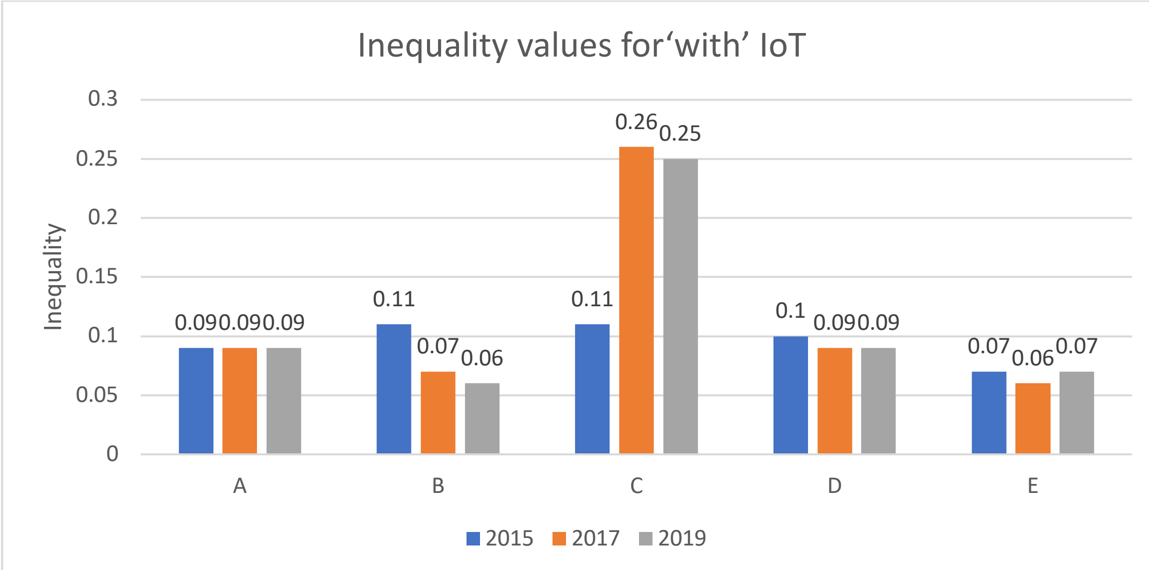

Figure 5. Inequality Values Using Accessibility of The Rail Line 'with' IoT

Table 2 shows differences in inequality values, which measure performance metrics such as service quality, efficiency, or other key performance indicators, with and without the implementation of IoT technology. In this context, a positive value would indicate that performance has declined with IoT implementation, while a negative value would suggest an improvement.

A more detailed analysis of the data in Table 2 shows the following:

- Rail Line A consistently shows negative values, indicating that IoT implementation has led to an improvement in performance across all years.
- Rail Line B shows a significant positive difference in 2015, followed by a negative value in 2017 and a slight positive value in 2019, suggesting variability in the impact of IoT over time.
- Rail Line C starts with a high positive difference, improves drastically in 2017, but then shifts back to a slight negative value in 2019, indicating inconsistent performance with IoT over the years.
- Rail Line D shows minor positive differences, indicating a slight decline in performance with IoT.
- Rail Line E shows improvement with IoT implementation over time, apart from 2019 where performance slightly declines.

Table 3 categorizes the rail lines as 'winners' or 'losers' based on the values from Table 2, with 'winners' having positive values (indicating worse performance with IoT) and 'losers' having negative values (indicating improved performance with IoT). Therefore, the following is deduced from Table 3:

- Rail Line A is consistent in being a 'loser', which in the context of these tables means it benefits from IoT with improved performance.
- Rail Line B oscillates between 'winner' and 'loser', suggesting it may not have consistently leveraged IoT for performance gains.
- Rail Line C is mostly a 'winner', except in 2019, when it becomes a 'loser', reflecting a positive impact of IoT in the final year.
- Rail Line D is a consistent 'winner', meaning that IoT did not improve performance, or possibly even degraded it.
- Rail Line E, like B, shows variability in its performance impact from IoT, ending as a 'loser' in 2019, thus benefiting from IoT implementation that year.

From the perspective of performance persistence analysis, we would expect a rail line that is well-managed and leverages IoT effectively to show consistently as a 'loser' in these tables, indicating sustained performance improvements. The variability in 'winner' and 'loser' status for some lines may suggest either a fluctuation in the effective use of IoT or the influence of external factors not controlled by IoT implementation. Consistent 'winner' status, paradoxically, might indicate challenges in adapting to or integrating IoT technologies effectively to improve performance.

Table 2. Differences in Inequality Values (scenario 'without' IoT minus 'with' IoT) for Rail Line for Years 2015, 2017, and 2019

Rail Line	2015	2017	2019
A	-13.96	-12.93	-13.67
B	38.64	-2.21	5.49
C	58.85	5.07	-0.26
D	10.33	10.27	9.10
E	8.11	8.66	-0.42

Table 3. Potential Winners (+ve value in Table 2) and Losers (-ve value in Table 2)

Rail Line	2015	2017	2019
A	Loser	Loser	Loser
B	Winner	Loser	Winner
C	Winner	Winner	Loser
D	Winner	Winner	Winner
E	Winner	Winner	Loser

The odds ratio for the winners and losers was found to be infinity from 2015 to 2017 and 0.5 for the years 2017 to 2019, thus indicating that a winning (or losing) rail line remained a winner from 2015 to 2017, while a winning rail line became a losing line (and vice-versa) from the year 2017 to 2019.

From the charts and tables above, we can infer that IoT has had a positive impact on accessibility and has the potential to reduce inequality in service levels. However, the performance persistence analysis suggests that the benefits of IoT are not uniform across all rail lines or over time. Rail Line B's fluctuating accessibility values with IoT and Rail Line C's persistent inequality despite IoT adoption illustrate that the integration of technology does not automatically translate to consistent improvements in service equity. These disparities could be due to a range of factors, including the initial state of infrastructure, the effectiveness of IoT integration, and external influences not captured by the data.

4. Summary & Conclusions

This study presented a comprehensive analysis of the LA Metro Rail lines, focusing on the potential impact of IoT technology on service connectivity and accessibility and on inequality in transit services. It demonstrated that IoT implementation would result in higher accessibility values across all rail lines over the years studied (2015, 2017, and 2019), indicating significant improvements in service accessibility due to technological advancements.

However, taking into consideration the low-income population residing close to the transit rail line station, the effects of IoT on reducing service inequality were not uniform across all lines or over time. Notably, Rail Line B showed fluctuating accessibility values with IoT, and Rail Line C exhibited persistent inequality if IoT deployment was undertaken. These variances suggest that while IoT has the potential to enhance service quality, its effectiveness could be influenced by a myriad of factors including the potential ridership (through population residing close to transit stations) and the integration process of IoT technologies.

The findings underscore the potential of IoT technologies to improve public transit by making it more accessible and efficient. Yet, the uneven benefits observed across different rail lines highlight the complexities involved in technology deployment in public infrastructure. The persistence of inequality in service levels, even with IoT adoption, calls for a planned approach to implementing technological solutions.

The disparity in the impact of IoT suggests that technology alone may not suffice to address systemic issues within public transit systems. Factors such as infrastructure readiness, socioeconomic conditions of the transit system's users, and the strategic integration of technology must be considered to achieve more equitable outcomes.

Further research should explore the conditions under which IoT technologies can most effectively contribute to reducing service inequality. Longitudinal studies could provide deeper insights into the sustainability of improvements in accessibility and service quality over time.

Comparative studies across different transit systems could highlight best practices for IoT integration in public transit. Understanding the role of infrastructure, user engagement, and policy frameworks in mediating the benefits of technology could guide more effective implementations.

There is a need for developing inclusive strategies that consider the diverse needs of all transit users, particularly marginalized communities, to ensure equitable access to improved services. This involves not only technological upgrades but also infrastructural improvements, policy interventions, and community engagement efforts to address broader issues of inequality in urban mobility.

Bibliography

Agarwal, V., & Naik, N. Y. (2000). Multi-period performance persistence analysis of hedge funds. *Journal of Financial and quantitative Analysis,* 35(3), 327-342.

Bröcker, J., Korzhenevych, A. & Schürmann, C. (2010). Assessing spatial equity and efficiency impacts of transport infrastructure projects. *Transportation Research Part B: Methodological*, *44(7),* 795-811.

Chandra, S., Braughton, M., Galicia, L. D., Sanchez, A., Medina, M., & Aldrete, R. (2016). A multi-modal transportation score to evaluate infrastructure supply-demand for commuters. *Procedia Engineering*, 145, 304-311.

Chandra, S., & Mazin, R. (2020). Quantifying rail transit investments with appropriate measures and metrics. *World Review of Intermodal Transportation Research*, 9(4), 313-333.

Chandra, S., Naik, R. T., & Galbeno, L. (2018). Impact assessment of the Internet of Things on feeder transit performance. *Transportation Planning and Technology*, 41(8), 830-844.

Chandra, S., & Narayanaswami, S. (2024). Framework for Rail Transport Inequality Assessment: A Case Study of the Indian Railway Zones with Superfast Express (SE) Trains. Available at SSRN 4850001.

Chandra, S., & Vadali, S. (2014). Evaluating accessibility impacts of the proposed America 2050 high-speed rail corridor for the Appalachian Region. *Journal of Transport Geography*, 37, 28-46.

Chavhan, S., Gupta, D., Chandana, B. N., Khanna, A., & Rodrigues, J. J. (2019). IoT-based context-aware intelligent public transport system in a metropolitan area. *IEEE Internet of Things Journal*, 7(7), 6023-6034.

Chen, T., Chen, Y., Zhou, Y., & Guo, J. (2022, March). The Efficiency Evaluation of Transit-oriented Development Focusing on an Integrated Multi-mode Public Transport System. *In 2022 7th International Conference on Big Data Analytics (ICBDA)* (pp. 280-289). IEEE.

Chen, Z., & Haynes, K. (2017). Impact of high-speed rail on regional economic disparity in China. *Journal of Transport Geography,* 65, 80–91.

Constantin, D. L., Nastacă, C. C., & Geambasu, E. (2021). Population accessibility to rail services. Insights through the lens of territorial cohesion. *Regional Science Inquiry*, 13(1), 81-98.

Cowell, F.A. (2006), "Theil, Inequality Indices and Decomposition", Creedy, J. and Kalb, G. (Ed.) Dynamics of Inequality and Poverty (*Research on Economic Inequality,* Vol. 13), Bingley: Emerald Group Publishing Limited, 341-356.

"Data." Longitudinal Employer - Household Dynamics (LEHD), 2019. https://lehd.ces.census.gov/data/

Fan, Y., Guthrie, A. & Levinson, D. (2012). Impact of light-rail implementation on labor market accessibility: A transportation equity perspective. *Journal of Transport and Land Use,* 5(3), 28-39.

Fraga-Lamas, P., Fernández-Caramés, T. M., & Castedo, L. (2017). Towards the Internet of smart trains: A review on industrial IoT-connected railways. *Sensors,* 17(6), 1457.

Fujita, M., & Thisse, J. F. (1996). Economics of agglomeration. *Journal of the Japanese and international economies,* 10(4), 339-378.

Golbeck, J. (2013). Network structure and measures. Analyzing the social web, 25-44. "Interactive Estimated Ridership Stats, LA Metro." Accessed November 20, 2022. https://isotp.metro.net/MetroRidership/IndexRail.aspx

Gutiérrez, J. (2001). Location, economic potential and daily accessibility: An analysis of the accessibility impact of the high-speed line Madrid–Barcelona–French border. *Journal of Transport Geography,* 9(4), 229-242.

Karou, S., & Hull, A. (2014). Accessibility modelling: Predicting the impact of planned transport infrastructure on accessibility patterns in Edinburgh, UK. *Journal of Transport Geography,* 35, 1-11.

Kim, E., & Yi, Y. (2019). Impact analysis of high-speed rail investment on regional economic inequality: A hybrid approach using a transportation network-CGE model. *Journal of Transport Economics and Policy (JTEP),* 53(3), 314-333.

Kim, K. (2000). High-speed rail developments and spatial restructuring: A case study of the Capital region in South Korea. *Cities 17* (4), 251–262.

Kyriazis, D., Varvarigou, T., White, D., Rossi, A., & Cooper, J. (2013, June). Sustainable smart city IoT applications: Heat and electricity management & Eco-conscious cruise control for public transportation. *In World of Wireless, Mobile and Multimedia Networks (WoWMoM), 2013 IEEE 14th International Symposium and Workshops,*1-5.

"LA Metro". Accessed on November 19, 2022. https://developer.metro.net/gis-data/ "Los Angeles Union Station, California High Speed Rail Authority". Accessed on February 2, 2018. http://www.hsr.ca.gov/programs/station_communities/la_station.html

Liu, S., Wan, Y., & Zhang, A. (2020). Does China's high-speed rail development lead to regional disparities? A network perspective. *Transportation Research Part A: Policy and Practice,* 138, 299-321.

Luo, H., & Zhao, S. (2021). Impacts of high-speed rail on the inequality of intercity accessibility: A case study of Liaoning Province, China. *Journal of Transport Geography, 90,* 102920.

Mishra, S., Welch, T. F., & Jha, M. K. (2012). Performance indicators for public transit connectivity in multi-modal transportation networks. *Transportation Research Part A: Policy and Practice,* 46(7), 1066-1085.

Misra, A., Gooze, A., Watkins, K., Asad, M., & Le Dantec, C. (2014). Crowdsourcing and its application to transportation data collection and management. *Transportation Research Record: Journal of the Transportation Research Board*, (2414), 1-8.

Monzón, A., Ortega, E., & López, E. (2013). Efficiency and spatial equity impacts of high-speed rail extensions in urban areas. *Cities* 30, 18-30.

Patel, D., Narmawala, Z., Tanwar, S., & Singh, P. K. (2019). A systematic review on scheduling public transport using IoT as tool. *Smart innovations in communication and computational sciences,* 39-48.

Perk, V., Flynn, J., & Volinski, J. M. (2008). *Transit ridership, reliability and retention,* (No. NCTR-776-07).

Taylor, B. D., Miller, D., Iseki, H., & Fink, C. (2009). Nature and/or nurture? Analyzing the determinants of transit ridership across US urbanized areas. *Transportation Research Part A: Policy and Practice,* 43(1), 60-77.

"The Internet of Things, 2015 OST-R Transportation Technology Scan: A Look Ahead." Office of the Assistant Secretary for Research and Technology, United States Department of Transportation. Accessed on June 21, 2016.

Theil, H. (1967). Economics and information theory (No. 04; HB74. M3, T4.).

Watkins, K. E., et al. (2011). "Where Is My Bus? Impact of mobile real-time information on the perceived and actual wait time of transit riders." *Transportation Research Part A: Policy and Practice* 45(8), 839-848.

Wu, W., Zheng, S., Wang, B., & Du, M. (2020). Impacts of rail transit access on land and housing values in China: A quantitative synthesis. *Transport Reviews,* 40(5), 629-645.

Zhao, P., & Li, P. (2019). Travel satisfaction inequality and the role of the urban metro system. *Transport Policy,* 79, 66-81.

Zhao, Y., Yu, X., Chen, M., Zhang, M., Chen, Y., Niu, X., ... Li, W. J. (2020). Continuous monitoring of train parameters using IoT sensor and edge computing. *IEEE Sensors Journal*, 21(14),15458-15468.

Zhou, J., Yang, L., & Li, L. (2018). The implications of high-speed rail for Chinese cities: Connectivity and accessibility. *Transportation Research Part A: Policy and Practice*, 116, 308-326.

About the Authors

Shailesh Chandra, PhD

Dr. Chandra is an associate professor in the Department of Civil Engineering and Construction Engineering Management at California State University, Long Beach (CSULB). He obtained his MS and PhD in civil engineering from Texas A&M University in 2009 and 2012, respectively. Dr. Chandra has more than 16 years of experience in transportation research focused on transport connectivity, transportation economics, accessibility, urban freight, and sustainability. He has been a principal investigator for several projects funded by various transportation agencies including the California Department of Transportation (Caltrans) and the United States Department of Transportation (USDOT).

Robert Valencia

Mr. Valencia is an undergraduate student in the Department of Civil Engineering and Construction Engineering Management at CSULB. His research interests relate to transportation data analysis, freight transportation and sustainability.

Vamsi Krishna Oruganti

Mr. Oruganti is a graduate student in the Department of Computer Engineering and Computer Science at CSULB. His research interests relate to programming, data analysis and transportation.

MTI FOUNDER

Hon. Norman Y. Mineta

MTI BOARD OF TRUSTEES

Founder, Honorable Norman Mineta***
Secretary (ret.),
US Department of Transportation

Chair, Jeff Morales
Managing Principal
InfraStrategies, LLC

Vice Chair, Donna DeMartino
Retired Transportation Executive

Executive Director, Karen Philbrick, PhD*
Mineta Transportation Institute
San José State University

Rashidi Barnes
CEO
Tri Delta Transit

David Castagnetti
Partner
Dentons Global Advisors

Maria Cino
Vice President
America & U.S. Government
Relations Hewlett-Packard Enterprise

Grace Crunican**
Owner
Crunican LLC

John Flaherty
Senior Fellow
Silicon Valley American
Leadership Form

Stephen J. Gardner*
President & CEO
Amtrak

Ian Jefferies*
President & CEO
Association of American Railroads

Diane Woodend Jones
Principal & Chair of Board
Lea + Elliott, Inc.

Priya Kannan, PhD*
Dean
Lucas College and
Graduate School of Business
San José State University

Will Kempton**
Retired Transportation Executive

David S. Kim
Senior Vice President
Principal, National Transportation
Policy and Multimodal Strategy
WSP

Therese McMillan
Retired Executive Director
Metropolitan Transportation
Commission (MTC)

Abbas Mohaddes
CEO
Econolite Group Inc.

Stephen Morrissey
Vice President – Regulatory and
Policy
United Airlines

Toks Omishakin*
Secretary
California State Transportation
Agency (CALSTA)

April Rai
President & CEO
Conference of Minority
Transportation Officials (COMTO)

Greg Regan*
President
Transportation Trades Department,
AFL-CIO

Rodney Slater
Partner
Squire Patton Boggs

Paul Skoutelas*
President & CEO
American Public Transportation
Association (APTA)

Kimberly Slaughter
CEO
Systra USA

Tony Tavares*
Director
California Department of
Transportation (Caltrans)

Jim Tymon*
Executive Director
American Association of
State Highway and Transportation
Officials (AASHTO)

Josue Vaglienty
Senior Program Manager
Orange County Transportation
Authority (OCTA)

* = Ex-Officio
** = Past Chair, Board of Trustees
*** = Deceased

Directors

Karen Philbrick, PhD
Executive Director

Hilary Nixon, PhD
Deputy Executive Director

Asha Weinstein Agrawal, PhD
Education Director
National Transportation Finance
Center Director

Brian Michael Jenkins
National Transportation Security
Center Director

MINETA TRANSPORTATION INSTITUTE