NATIONAL CENTER FOR UNDERSTANDING FUTURE
TRAVEL BEHAVIOR AND DEMAND

Final Project Report

The Effects of Street Repurposing on Pedestrian, Vehicle and Visitor Patterns

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July 2025

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.	
N/A	N/A	N/A	
4. Title and Subtitle The Effects of Street Repurposing on Pedestrian, Vehicle and Visitor Patterns		**5. Report Date** July 31, 2025 **6. Performing Organization Code** N/A	
7. Author(s) Lyra Chen, Ph.D. Cynthia Chen, Ph.D. Steve Mooney, Ph.D.		**8. Performing Organization Report No.** N/A	
9. Performing Organization Name and Address Department of Civil and Environmental Engineering University of Washington 201 More Hall, Seattle, WA		**10. Work Unit No. (TRAIS)** N/A **11. Contract or Grant No.** 69A3552344815 and 69A3552348320	
12. Sponsoring Agency Name and Address U.S. Department of Transportation, University Transportation Centers Program, 1200 New Jersey Ave, SE, Washington, DC 20590		**13. Type of Report and Period Covered** Final Report, 2024-2025 **14. Sponsoring Agency Code** USDOT OST-R	
15. Supplementary Notes N/A			

16. Abstract

This research advances the field of urban mobility by making detailed analyses of the traffic and economic impacts of several different street repurposing projects in Seattle. Using data from Location-Based Services (LBS), the authors evaluate the repurposed street segments in terms of the changes on pedestrian and vehicle traffic, the times visitors were spending right around those streets, and the various kinds of people (socio-demographic). They're looking primarily at interventions in Seattle: Ballard Ave Café Street (2020) and improvements (2022), U-District Outdoor Café (2021) and Green Street (2024), First Ave Public Seating (2023), and Taylor Ave Pickleball Court (2023). The finer-scale approach captures localized behavioral changes and provides insights into visitors' movement patterns. The study establishes a framework for combining granular mobility and economic analyses, guiding future research to refine LBS data applications and informing policies for vibrant urban spaces. Key findings reveal that curbside dining and public seating significantly increase pedestrian activity and local business, particularly in retail districts, while well-planned street reconfigurations maintain vehicle flow without congestion. Seasonal interventions require alignment with community-active periods, and small-scale recreational projects need targeted marketing to maximize impact.

17. Key Words		18. Distribution Statement	
Street Furniture, Street Repurposing, Pedestrian Mobility, Urban Design, Big Data, Location-Based Service (LBS) Data		No restrictions.	
19. Security Classif.(of this report)	**20. Security Classif.(of this page)**	**21. No. of Pages**	**22. Price**
Unclassified	Unclassified	40	N/A

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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ACKNOWLEDGMENTS

This research was partially supported by the National Center for Understanding Future Travel Behavior and Demand (TBD), a National University Transportation Center sponsored by the U.S. Department of Transportation (USDOT) under grant numbers 69A3552344815 and 69A3552348320. The authors would like to thank the TBD National Center, USDOT, for their support of university-based research in transportation, particularly for the funding provided for this project.

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EXECUTIVE SUMMARY

This study evaluates the impact of innovative urban infrastructure changes implemented in Seattle, with a focus on block-level interventions such as sidewalk cafes, reallocated street space for outdoor dining, and street redesigns to support diverse uses, such as commercial, social, or recreational uses. Leveraging Location-Based Service (LBS) data, Google Street View, satellite imagery, and census and business data, the study analyzes pedestrian and vehicle traffic patterns and visitor behavior in sites including Ballard Ave, University District (U-District) Green Street and Plaza, First Ave Public Seating, and Taylor Ave Pickleball Courts.

Workflows and algorithms were developed to process and integrate these diverse datasets, and various metrics were also introduced to quantify changes in infrastructure and mobility. Key findings indicate that curbside dining and public seating significantly increased pedestrian activity and local business in retail-heavy areas, with Ballard Ave Café Street and First Ave Public Seating showing notable increases in staying pedestrians and weekly visits. Well-planned street reconfigurations maintain vehicle flow without congestion, and seasonal interventions like the U-District Green Street required alignment with community-active periods for success. Small-scale recreational projects, such as Taylor Ave Pickleball Court, needed targeted marketing to maximize impact.

The project delivers open-source tools and visualizations that support data-driven planning and policy, offering insights for future urban mobility and public space design. This interdisciplinary effort, combining transportation engineering, public health, and computer science, establishes a framework for evaluating block-level urban interventions.

INTRODUCTION

The COVID-19 is a crisis that is unanticipated both in its occurrence and its length of impact. In the early stages of the pandemic, many disease mitigation measures, such as social distancing, reduced retail operation hours, and work-from-home arrangements, have been implemented by office employers and retail businesses. These interventions, however, resulted in economic and societal costs, as commuters no longer visited downtowns, leading to a decline in customer traffic for nearby retail businesses and the desertion of downtown areas. To overcome the challenges, many cities modified transportation infrastructure and repurposed street spaces by installing street furniture, especially allowing sidewalk cafes and patios for outdoor dining, re-orienting benches to avoid face-to-face seating, and reallocating street space to accommodate non-motorized modality (biking or walking) users and redesigning the street network for easy travel and parking access. Government agencies aided the speedy installation of such street furniture with a fast permit application process. Some of these furniture were converted into permanent fixture to meet community needs (Dean et al., 2023). Together, these actions aim to cultivate a safe and welcoming environment for customers such that more visits (primarily via non-motorized modes) and economic activities can be drawn to the area, thus reviving the deserted downtown.

As cities transition into the post-COVID era and envision the future of our urban cores and travel behavior, street design innovations are under heated discussion, which leads to a series of questions: What are the effects of these urban infrastructure innovations? How well do they draw visitors and support businesses nearby? What are their effects on the region's traffic patterns? Are there spillover effects spatially? Answers to these questions are critical, as the insights can influence a wide range of urban planning, policy, and community decisions. Urban and transportation planners require this information for designing pedestrian-friendly environments and balancing the needs of various users. City officials and policymakers need this insight to make informed decisions on future infrastructure investments and urban policies. Business owners, especially those in urban areas where the street was repurposed (e.g., restaurants using outdoor seating, retailers benefiting from more pedestrian traffic) need data on how these changes affect foot traffic, sales, and their operations. Local residents and community members are to be ensured that street reconfiguration meets their needs and preferences. Researchers conducting studies on urban mobility, public space usage, or post-pandemic city design need data to further analyze trends and propose evidence-based solutions.

The existing literature has a wealth of knowledge on how the built environment affects travel behavior. The theoretical frameworks behind the correlation between urban infrastructure innovations and travel behavior are supported in the built environment and design literature. Specifically, a widely accepted framework is the 3D's (density, diversity, and design) in the built environment, proposed by Cervero and Kockelman (1997). Per the definition from Cervero and Kockelman (1997), density has three dimensions, population, employment, and accessibility to jobs measured in a gravity-decay model. Diversity refers to the dissimilarity in land uses within a tract, proportion of commercial/retail parcels, proximity to commercial/retail uses, etc. And design includes street network patterns, pedestrian and cycling provisions, parking availability's etc. This framework supports the assertion that pedestrian-oriented designs such as increasing sidewalk width, signalizing street crossings and street trees can significantly encourage non-motorized travel. This framework was later expanded into 5Ds (Reid Ewing & Robert Cervero, 2010) with the additional 2Ds (destination accessibility and distance to transit).

Specifically focusing on design, Bürdek (2015) proposed the three functions of design that affects travel behavior: practical, aesthetic, and emblematic (Blitz & Lanzendorf, 2020). In the context of the built environment and street innovations, practical function refers to how effectively a street fulfills its intended purpose and usefulness catering to user's requirements, including operation, durability, and safety features. For example, a sturdy outdoor patio fulfills the practical function to serve outdoor dining customers. The aesthetic function relates to visual presentations and attractiveness or beauty of furniture through features such as symmetry, conciseness, and order (Stamps, 2000). Thus, repainted street strips are considered aesthetically functional. Lastly, emblematic function considers the association evoked that reflects individual preference, self-realization and social-economical context (Blitz & Lanzendorf, 2020). This functionality can be seen as the hospitality of neighborhoods that adopt street furniture or space repurpose.

Building on these two frameworks, existing studies tackled these questions in a multi-disciplinary approach involving transportation engineering, built environment, urban planning, and architecture. For example, Cervero and Kockelman (Robert Cervero et al., 1997) selected 50 census tracts' travel survey in the San Francisco Bay area in 1990-1991 and suggested compact, mixed-use, pedestrian-friendly designs can discourage vehicle trips, reduce VMT per capita, and encourage non-motorized travel. Similarly, Salazar Miranda et al. (2021) looked at the Global Positioning System (GPS) traces to understand how people move in the city, combining with computer vision techniques to measure the built environment's features that might motivate these choices. And several analyses from Siu and Wong, Mehta, Sisiopiku and Akin (Mehta, 2008; Sisiopiku & Akin, 2003; Siu & Wong, 2015) collect qualitative data through news articles and policy document review, field observation, interviews with government officers.

The existing literature, however, is nearly exclusively at the larger scale of census tracts, rather than at the block-level where the presence of street furniture or redesign are located. There is little to no insight into how block-level urban infrastructure innovations lead to changes in visit patterns as well as nearby businesses. And yet, changes at this scale (block-level) are where local policy implementations take place. Further, the prevailing datasets include travel diaries, surveys, interviews, and policy documents, which are static and cross-sectional. Using these datasets, at best, one can compare different behavioral patterns among locations with different built environment features, not before and after study. Therefore, this study is motivated to understand the above questions using block-level, longitudinal data that captures before and after changes in urban infrastructure to understand the travel behavior changes associated with street furniture and redesign.

To achieve this, our research employs a big data-oriented experimental design framework, leveraging passively generated GPS data to capture aggregate travel demand at street and block level. Additionally, we utilize time-series street-view imagery, e.g., Google Street View and satellite images, to capture changes in urban infrastructure, to verify modifications to the pedestrian right-of-way, thereby validating the observed shifts in urban landscape use. The framework also accounts for external factors that might influence travel demand, including weather conditions, economic shifts, and ongoing public health crises, to isolate the effects of the pandemic-induced urban design changes.

LITERATURE REVIEW

Historically, vehicle traffic on the streets is the primary focus of urban planning in the U.S. (Brown et al., 2009). For the last 50 years, urban street design has shifted from a focus on vehicular traffic to the creation of spaces that work for people. Since the late 20th century, an approach known as "Complete Streets" has been taken up by numerous cities across the country (McCann et al., 2023). This framework seeks to create streets that are safe, accessible, and convenient for all users, including but not limited to pedestrians, cyclists, motorists, and transit riders (National Complete Streets Coalition, 2025). Cities now routinely repurpose street space by introducing pedestrian plazas, parklets, street furniture, and car-free events to support recreation, commerce, and people-centric uses (Nelson & Hibberd, 2024).

The historical shift from car-centric to people-centric designs reflects changing societal priorities toward improved safety, public health, economic vitality, and environmental sustainability and livability. Over the past few decades, numerous studies have explored how streets design, which prioritize safe and accessible travel for pedestrians, cyclists, motorists, and transit users, influence traffic, travel behaviors, and local businesses.

The research evaluating the impacts of street redesigns and repurposes on traffic and mobility has shown that street redesigns that make space for pedestrians, cyclists, and other public uses of the street can result in some very positive changes. Interventions such as road diets, shared streets, pedestrian plazas, and sidewalk cafés have led to fewer vehicles in the street, more people walking and cycling, and more people using the street in all its public dimensions (Ewing & Dumbaugh, 2009; Marshall & Garrick, 2010; Nello-Deakin, 2022). The studies usually use several methods in combination: automatic traffic counting devices, manual counting of cyclists and pedestrians, and GPS-based vehicle tracking. They make before-and-after comparisons, using control sites to better assess the results of not only the kinds of people moving through the streets but also the kinds of vehicles. In before-and-after studies of the kinds of vehicle volume reductions that have occurred in cities like Barcelona and San Diego, researchers have found that reductions range from 10% and up to over 50%. Moreover, they have found that adjacent streets experience minimal spillover (Buehler & Dill, 2016). In numerous instances, speed reductions of 10-20% were observed, resulting in much safer streets and more user-friendly conditions for all kinds of street users. Some studies utilized more advanced difference-in-differences or time-series regression models to better handle seasonal issues and the general uptick in street activity post-COVID. These methods allow researchers to hypothesize more confidently about causation rather than correlation.

Studies of business and economic impact have found generally neutral to positive effects on local commerce from street redesigns that are more pedestrian-friendly and inviting to public life. In cities such as Barcelona and several other Spanish urban centers, projects to create pedestrian-friendly areas have been associated with significant boosts in sales and other business metrics, the very best results have been registered by restaurants and cafés (Yoshimura et al., 2022; Zhang et al., 2024). A thesis study by Osterhage (2024) in Seattle looked at street redesigns done under the Vision Zero program and found that they did not harm the revenues of nearby businesses, even in places where direct vehicle access was diminished. The investments in bicycle and pedestrian infrastructure usually support or enhance the economic outcomes for businesses that are close to them (Volker & and Handy, 2021). These studies often use a mix of data sources, including store-level transaction data, municipal sales tax records, business surveys, and commercial vacancy rates.

Analytical approaches include quasi-experimental designs like difference-in-differences estimation, propensity score matching, and pre/post comparison of economic indicators.

Despite these positive trends, several aspects of the current literature limit our ability to generalize and to use these findings across a wider variety of planning situations. Literature lacks integrated analyses that assess, all at once, the mobility, economic, and social outcomes of street reconfiguration. Very few studies collect and analyze, at the same time, how well the businesses along that street are doing. This fragmentation limits our understanding of the effects that design changes have on the urban system and its various stakeholders. To bridge these gaps, we need to evaluate fine-scale mobility data (pedestrian flows, vehicle counts, and speeds) as well as business metrics (e.g., visits and their dwell times) to get a better insight into the impact of street repurpose in urban areas.

Location-based service (LBS) data, derived from mobile devices and GPS-enabled applications, has emerged as a powerful tool for analyzing urban mobility patterns. Unlike traditional methods such as surveys or manual counts, LBS data provides real-time, high-resolution insights into pedestrian and vehicle movements. Studies have used LBS data to measure pedestrian flow in response to street interventions (Nam et al., 2024). Additionally, LBS data has been employed to assess traffic speed and congestion, offering a more dynamic understanding of mobility than static sensors (Soole et al., 2023). LBS data offers unparalleled opportunities for evaluating the effects of street repurpose in real time. The use of LBS data enables more precise and scalable analyses than traditional approaches, offering a comprehensive, data-driven examination of street repurposing's multifaceted impacts, contributing to the growing body of knowledge on urban mobility and livability.

DATA

Study Sites

The city of Seattle is leading the way in reconsidering how streets function in the urban environment. During the COVID-19 pandemic, initiatives like Stay Healthy Streets and Safe Start permits brought about a number of changes that shifted public use of streets in the direction of more adaptable, livable spaces (Seattle Department of Transportation, 2025). Many of these changes evolved into long-term programs (e.g., Café Streets). In our study we looked at multiple locations in Seattle where the streets were reconfigured for commercial (e.g., curbside café), social (e.g., public seating), and recreational (e.g., pickleball court) uses. We choose study sites by screening google street view datasets, satellite images, as well as consulting local cities for identification of additional sites in the region. The goal is to have a set of sites with contrasting characteristics in the built environment and socio-demographic characteristics. Figure 1 shows the before and after pictures of the study sites in Seattle from four projects, each of which has well documented details (as shown in Table 1) of the interventions and time of installation, which are necessary for our impact study.

Figure 1 Study Sites Before and After the Interventions Installation

Table 1 Interventions of the Street Repurposing Projects in Seattle

Project	Interventions	Time of Installation
Ballard Ave Café Street (2020, 2022)	• Ballard Ave between 20th Ave NW and 22nd Ave NW: 2020: Reconfigure from two-way to one-way; curbside cafes 2022: parking, loading, curb bulbs and sidewalk cafes	2020 Curbside Dining: SDOT opened permit applications on 7/29/2020 and the necessary street signage was installed on 9/1/2020 2022 Phase 1 Improvement: construction for 3 weeks 7/18/2022-8/7/2022
U-District Green Street and Plaza (2021, 2024)	• NE 43rd St between Brooklyn Ave and University Way: New sidewalks, roadway panels, curb ramps, and installation of the natural drainage system, new streetlights, and street trees, markings, and outdoor picnic tables. • NE 42nd St between Brooklyn Ave and University Way: Outdoor seating (picnic tables, Adirondack chairs, and umbrellas), trees and planters, street mural and art installation	NE 43rd St: Construction began in August 2020, picnic tables were installed in May 2021, and the street (west of University Way) remained closed to traffic until the U-District light rail station opened on 10/02/2021 NE 42nd St: Preparation of the activated area began in June, and summer activation lasted 3 months, July – September 2024
First and Battery Portal Porch Public Seating (2023)	• 1st Ave between Battery St and Bell St: Over-sized modular longitudinal seating and benches in solid and robust materials, round planters that will house trees and plants, solar powered pedestrian-scale lights	Work started on March 27, 2023, and open to public on August 25, 2023
Taylor Ave Pickleball Court Conversion (2023)	• Taylor Ave between Denny Way and 5th Ave/Vine St: Pickleball courts were assembled on city streets using 30′ x 60′ EasyRoll mats	The Pickleball for All event was on September 16th and 17th, 2023, and the two courts on Taylor Ave were made permanent after the event

LBS Location Data

Aggregated mobility data is provided by Cuebiq, a location intelligence platform. Data is collected from anonymized users who have opted-in to provide access to their location data anonymously, through a CCPA and GDPR-compliant[1] framework. Through its Social Impact program, Cuebiq provides mobility insights for academic research and humanitarian initiatives. In order to better preserve the privacy of users, the data vendor applied privacy enhancements to the data, using the data vendor's patented Privacy Enhanced Mobility (PEM) methodology: all blacklisted locations (sensitive POIs) are filtered out, all recurring areas (home or work) are uplevelled (uplevelling means transforming the original (latitude, longitude) data into the centroid of the census block group covering the location point), and all whitelisted and other locations are kept. The data vendor also provides inferred stops, trajectories and visit data. The device location data in our study has a median time gap (the time duration between two consecutive pings of a device) of 1 minute (90% 10 minutes), median spatial gap (the distance between two consecutive pings of a device) of 90-100 meters, and the median accuracy radius of 15 meters (90% within 100 meters).

The Cuebiq responsible data sharing framework enables research partners to query anonymized and privacy-enhanced data, by providing access to an auditable, on-premise Data Cleanroom environment. All final outputs provided to partners are aggregated in order to preserve privacy. We query the database by finding devices that have at least one location record inside the study area (street segment or census block group level) during our study periods. All of the device's locations (pings) on the date when the device visited or passed through the study area will be collected for further inference of travel pattern and home or work locations of the user (device). The devices and the locations data were retrieved for all the study sites and control sites, both at street segment level and Census block group level, during the before period and after periods, from the database on the data vendor's platform.

External and Ground Truth Data

In addition to the core location data, street view images and geography data (e.g., Seattle's Street network and sidewalk data) is essential to map infrastructure changes and their spatial effects, land use data provides context for economic activity variations across commercial and residential areas, and census and socio-demographic data are crucial to analyze visitor demographics and inclusivity shifts. Other external data such as the Seattle weather data during the study periods are also collected for modeling.

Ground truth data, such as manual pedestrian counts, is also collected for validation to ensure the accuracy and reliability of LBS-derived metrics against observed realities. In our study the ground-truth data, including the personal trips data and manual counts, e.g., the Public Life data (moving and staying pedestrians at some selected locations) by Seattle Department of transportation, were collected for validation purposes.

[1] **CCPA** (California Consumer Privacy Act) and **GDPR** (General Data Protection Regulation) are both privacy laws that regulate how organizations handle personal data.

ANALYSIS

Study Scope

The spatial and temporal scope of our study are designed as follows: for each of the study sites (Table 1), we selected a similar street (in terms of land use and traffic condition) as the control site. We manually geocoded the street segments of the study sites and control sites and identified the corresponding census block group by spatially joining the street segments with the census geography data. The time scope of study for each site includes the before period, during period (for example, the construction period, or the period when the implementation was announced and prepared), and after period when the intervention was ready and open to the public. We selected 12-week pre-intervention (before) and post-intervention (after) periods, carefully balancing the time required to capture behavioral change trends, the availability of data, and computational efficiency.

Research Design

Our research design is a five-step framework, as shown in Figure 2.

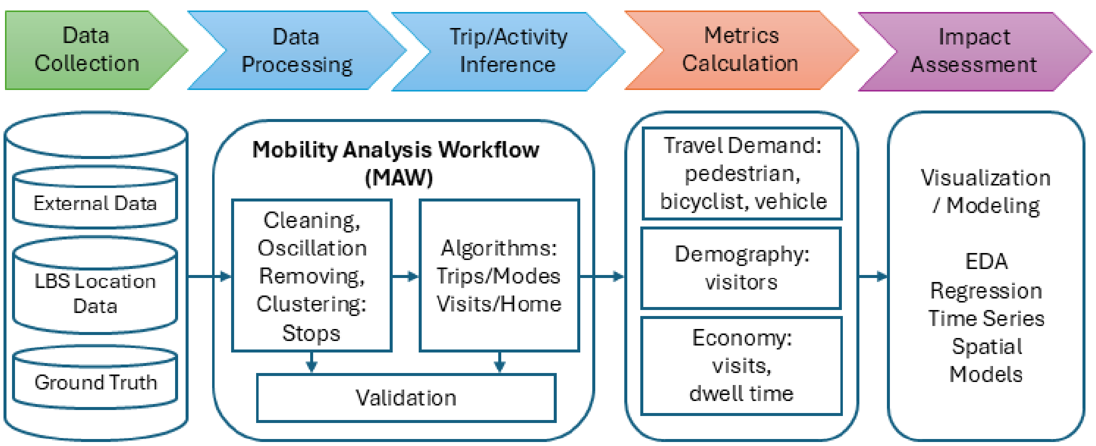

Figure 2 Research Framework for Street Repurposing Impact Analysis

- First, data collection involves collecting anonymized Location-Based Services (LBS) data, such as GPS traces and app-based geolocation records, from a study area (e.g., the street or census block group where the street repurposing was implemented) for pre- and post-intervention periods (e.g., 3 months before and after redesigns), ensuring comprehensive coverage of travel and visitor patterns. Other external data (e.g., weather, census data) and ground truth data (manual count of pedestrians) are collected as well.

- Second, data processing includes cleaning the underlying data by removing duplicates and outliers, applying spatial-temporal smoothing to eliminate oscillations (the phenomenon where a mobile device's recorded position appears to fluctuate or switch repeatedly between multiple locations over a short period, due to technical factors such as signal handovers between cell towers or GPS jitter, rather than actual user movement), and identifying stays, instances where a user/device remains in the same place for some time doing activities such as working, shopping, or staying at home etc. The stays are the foundation for the next step of trips and activity inferences.

- The third step includes segments trajectories into trips, which are movements from one stay (origin) to the next (destination), and detects travel modes (e.g., pedestrian, vehicle), while identifying visitor stays and home and work locations through point of interest (POI) mapping and stay analysis. The inferred trips or visits are compared against ground-truth data to ensure the validity of the data and robustness of the algorithms in this process.

- Fourth, metrics selection and calculation derives key indicators, including pedestrian and vehicle flow counts, vehicle speeds, visitor counts, dwell times, arrival time distributions, and socio-demographic profiles from Census Block Group data.

- Finally, impact assessment employs statistical methods, such as paired t-tests, difference-in-differences analysis, and time-series modeling, to compare pre- and post-intervention metrics, assessing changes in traffic flow and travel behavior.

LBS Data Processing and Travel Inference

Figure 3 shows a framework designed to analyze location-based data and infer travel information, including the stops, trips and modes, and home/work locations and visits.

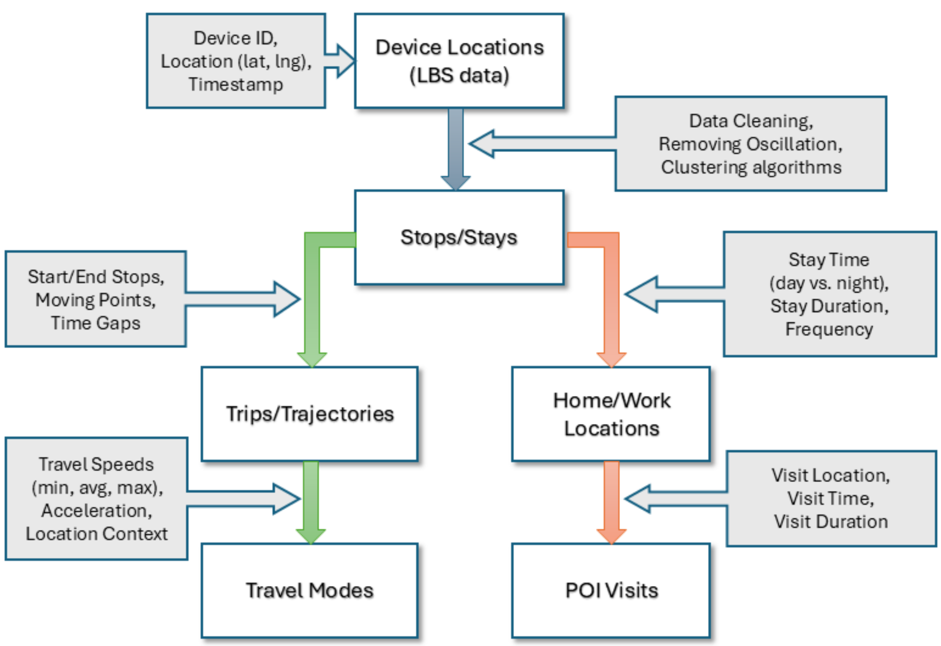

Figure 3 LBS Data Processing and Travel Inference Framework

- *Stops Inference*

The first core process is transforming LBS data into identified stops or stays. The Mobility Analysis Workflows (MAW) we used in our study to infer the stops (or stays) were developed by (Guan et al., 2022; Wang et al., 2019). Initially, LBS data undergoes cleaning to remove duplicates and outliers, followed by spatial-temporal smoothing to address oscillations (repetitive movements due to signal jitter), ensuring trajectories reflect true user behavior. Subsequently, a density-based spatial clustering algorithm is applied with a spatial radius (e.g., 0.2 km) and a minimum duration threshold (e.g., 15 minutes) to group closely spaced points into stay clusters, representing locations where users linger, such as homes or commercial points of interest. This step, validated against ground-truth data like person trips, produces a dataset of stays with associated durations and coordinates, forming the foundation for further mobility analysis. The algorithms and ways of determining the parameters are detailed in (Wang et al., 2019). Stop detection validation involves comparing inferred stops against personal trip data, such as travel diaries or GPS logs from a sample of individuals, to confirm that stay locations align with reported activities, achieving a high recall rate (e.g., >85%) as validated in studies like (Wang et al., 2019).

- *Trip and Mode Detection*

The transition from stops/stays to trip segmentation and mode detection involves segmenting the processed trajectories into distinct trips. Trips are identified by detecting transitions between stay clusters, defined by a minimum movement threshold (e.g., >100 meters) and a temporal gap (e.g., >30 minutes) to separate consecutive trips, filtering out noise from short movements. Mode detection then classifies each trip based on speed (e.g., <5 km/h for pedestrians, 5-25 km/h for bicycles, >25 km/h for vehicles) (Murtagh et al., 2021), and other factors being considered include acceleration and route alignment with infrastructure (e.g., bike lanes, or pedestrian only plaza). This process generates detailed trip data including start/end times, distances, durations, and inferred modes, enabling analysis of how street furniture influences travel patterns. In our study, trip and mode detection validation includes cross-checking inferred trips and modes (e.g., pedestrians) against manual counts of moving and staying pedestrians conducted at key street segments by Seattle Department of Transportation (SDOT) through the Public Life Data project, to see how different the manual counts data and the inferred trips are.

- *Home and Visit Identification*

The other step involves identifying home and work locations by analyzing the stay data to infer significant or recurring activity locations. Home locations are determined by clustering nighttime stays (e.g., 10 PM to 6 AM), with the most frequent cluster mapped to Census Block Group (CBG) boundaries via U.S. Census data to derive socio-demographic profiles. Work locations are similarly identified from frequent daytime stays (e.g., 9 AM to 5 PM) on weekdays. Visits, such as cafes or retail stores, are detected by mapping stay clusters in the study area, calculating visitor counts (unique devices/day), dwell times (stay duration), and arrival time distributions. The location data we are using are uplevelled (centroid of the CBG instead of the real home or work location) and the inferred home and work location are at the CBG level to protect privacy.

Metrics and Statistical Analysis

We selected and investigated the metrics as in Table 2.

Table 2 Metrics of Travel Patterns

Category	Metrics	Details
Traffic Patterns	*Pedestrian Flow*	Pedestrians (staying and moving) count during a time period (such as daily or weekly) on the street segment and within the census block group, reflecting foot traffic changes.
	Vehicle Flow	Vehicle trips per street segments during a time period (such as daily or weekly), assessing traffic volume shifts.
	Vehicle Speeds	Median vehicle speeds on treated street, indicating traffic calming or congestion
Visit Patterns	*Visitor Count*	The number of visitors during a period of time (such as daily or weekly) to various POIs inside a study area (such as street segments or a census block group), measuring economic activity.
	Visit Dwell Time	Average stay time duration of visits, reflecting engagement.
	Visit Arrival	Distribution of visits start times (time of the day and day of the week), capturing temporal shifts
	Visitor Home CBG Distribution	Proportion of visitors by CBG, number of unique home CBGs and distance distributions
	Visitor Socio-Demographic	Shifts in socio-demographics (e.g., income, age) in the home CBGs

In order to estimate the statistical effect of the intervention, we use Difference-in-Difference (DiD) regression model with the inclusion of covariates to control for confounding variables and better isolate the effect of the intervention from other factors that might influence the outcome. This adjusted formula:

$$Y_{it} = \beta_0 + \beta_1 Post_t + \beta_2 Treatment_i + \beta_3 (Post_t \times Treatment_i) + \gamma \mathbf{X} + \varepsilon_{it}$$

Where:

- Y_{it}: normalized outcome (e.g., pedestrian count) for street group *i* at time *t*.
- β_0: constant term.
- $Post_t$: 1 = post-intervention, 0 = pre-intervention, where coefficient β_1 estimates the effect of the time (post or pre-intervention).
- $Treatment_i$: 1 = treated street, 0 = control street, where coefficient β_2 estimates the effect of the street group (treated or control street).
- $Post_t \times Treatment_i$: Interaction term, where β_3 estimates the effect of the intervention, the coefficient of interest.
- **X**: vector of time-varying or fixed covariates (e.g., weekend, holiday, temperature, precipitation, or economic indicators), where γ is the coefficients on covariates.
- ε_{it}: error term.

In our study we normalize the outcome Y_{it} by scaling the observed values relative to the pre-intervention baseline average (transforms the raw outcome into a normalized metric, typically expressed as a percentage or ratio of the pre-intervention mean) to account for inherent differences across locations or time periods and mitigate biases from pre-existing disparities in pedestrian flow or visitor counts. In the normalized model, the value of β_3 reflects the percentage of change, aligning with urban design studies where relative improvements (e.g., percentage increase in pedestrian counts) are more meaningful than raw counts.

RESULTS

This section presents the findings of our study on the impact of street furniture and space repurposing, utilizing LBS data collected from selected sites and census block groups in Seattle over pre- and post-intervention periods. The analysis focuses on changes in pedestrian and vehicle traffic as well as visitor patterns following the implementation of street furniture and repurposed spaces. The results are organized into tables and figures to provide a clear and comprehensive overview of the observed trends and to offer insights into how urban design interventions influence mobility and economic activity.

Impacts on Traffic Patterns

The trends of weekly pedestrians and vehicles both at the census block group level and street segment level for Ballard Ave Café Street implementation in 2020 and Ballard Ave improvement in 2022 are shown in Figure 4 (the normalized count value in Figure 4-6 are based on the mean count of the street level, so as to get a consistent scale of the trends). We see a trend of decrease in pedestrian and vehicle counts during the study periods (before, during, and after the implementation) at the census block group level. However, we didn't observe the obvious trend of decrease at the street level. As shown in Table 3, when outdoor curbside café was first introduced on Ballard Ave in 2020, the staying pedestrian counts increased post-intervention on the treated street despite the decrease of greater than 10% at census block group level. For 2022 improvements on Ballard Ave, however, both street level and census block group level see a decrease in all pedestrian and vehicle counts. The DiD regression models (Table 3) confirm the significant increase of traffic including foot and vehicular traffic to the treated street (Ballard Ave in 2020) compared to the control street or the census block group, and the staying pedestrian counts increased the most. There is also a tendency to increase the number of staying pedestrians after the street improvement in 2022, however, the changes are insignificant.

The trends for First Ave Public Seating and Taylor Ave Pickleball Court (both implemented in 2023) are shown in Figure 5. For First Ave Public Seating, we see increases in pedestrian and vehicular traffic at both census block group and street level. The DiD model results also show that census block group experienced an increase greater increase than the street level for moving pedestrians and vehicles, while the staying pedestrians increase at street level exceeds the increase at census block group level, which indicates a potential of attracting more pedestrians staying in the public seating area. For Taylor Ave Pickleball Court, we don't see an increase in foot traffic for both site level and census block group level in Figure 5. The DiD model results even show a decrease in both staying and moving foot traffic in the treated site. This may need further investigation due to the small area of the treated site (2 pickleball courts in a very short street segment).

Changes for the U-District Outdoor Café in NE 43rd St (installed in 2021) and Green Street in NE 42nd St (implemented in 2024) are shown in Figure 6. We only collect the data for the before and after periods (not during the construction period) for NE 43rd St as the project on NE 43rd St started in August 2020, and the street was closed for construction and didn't open until June 2021. The DiD regression model results show a slight increase in the vehicle traffic count compared with the control street, and a significant increase in pedestrians compared with the census block group where the streets are located. The green street program at NE 42nd St in summer 2024 experienced decrease in the traffic count, especially at the census block group level. One possible reason is the timing of the green street program (July – September 2024), which is when the nearby University is on summer break and thus the visits to the treated area dropped significantly compared to the before period (March – May 2024).

We also checked the vehicle speed changes at the treated streets and the adjacent streets, for projects Ballard Ave Café Street and U-District Outdoor Café and Green Street, where the streets were reconfigured, e.g., from two-way to one-way at Ballard Ave. As shown in Figure 7, the median vehicle speeds at different time of the day for Ballard Ave were slower than the adjacent street (Leary Ave) in both before and after periods in 2020. We don't see vehicle traffic slow down for the after periods on both streets, except for morning peak hours (6am – 10am). The speeds of the two streets in 2022 following a similar trend as in 2020, with a slight slowdown during morning peak hours in Ballard Ave. We don't see speed reduction in Leary Ave in any time periods of the day. for U-District project, we check the median speeds on the treated streets (NE 43rd St in 2021 and NE 42nd in 2024) and the adjacent street (NE 47th St). We observe (in Figure 8) vehicle slowdown during midday (10am – 4pm) and afternoon peak hours (4pm – 8pm) on both the treated street (NE 43rd St) and adjacent street (NE 47th St) in 2021, while no slowdown observed on both treated street (NE 42nd St) and adjacent street (NE 47th St) during the two time periods (midday and afternoon) in 2024. In summary, no significant adverse effects (traffic slowdown due to congestion) were observed on the adjacent streets, while the changes of speeds on the treated streets are mixed, especially morning peak hours, which is likely due to the traffic calming treatment such as lane reduction (from two-way to one-way) on the treated streets.

Left: Ballard Ave 2020 **Right: Ballard Ave 2022**

Figure 4 Weekly Pedestrian and Vehicle Count Trend at Treated Site and Census Block Group (Ballard Ave)

Left: First Avenue Public Seating **Right: Taylor Ave Pickleball Court 2023**

Figure 5 Weekly Pedestrian and Vehicle Count Trend at Treated Site and Census Block Group (First Ave and Taylor Ave)

Left: U-District NE 43rd St 2020-2021 **Right: U-District NE 42nd St 2024**

Figure 6 Weekly Pedestrian and Vehicle Count Trend at Treated Site and Census Block Group (U-District)

Table 3 Pedestrian and Vehicle Count Changes and Values of Post-Treatment Coefficients (β_3) from Difference-in-Difference Regression Models

Study Site	Metrics (average daily count)	% Change		β_3 from DiD with covarites (normalized)		
		Site	CBG	Site-Site	CBG-CBG	Site-CBG
Ballard Ave Café Street (2020)	Total Devices	-2%	-18%	**0.17**	0.02	**0.14**
	Staying Pedestrians	3%	-15%	**0.23**	**0.08**	**0.14**
	Moving Pedestrians	-4%	-16%	**0.13**	0.04	**0.10**
	Moving Vehicles	-1%	-18%	**0.17**	0.02	**0.13**
Ballard Ave Café Street (2022)	Total Devices	-12%	-14%	-0.06	**-0.08**	0.03
	Staying Pedestrians	-21%	-27%	0.14	0.04	0.07
	Moving Pedestrians	-28%	-27%	0.00	0.00	0.00
	Moving Vehicles	-6%	-10%	**-0.20**	**-0.16**	0.03
U-District NE 43rd St (2021)	Total Devices	-46%	-57%	0.08	0.03	**0.12**
	Staying Pedestrians	-34%	-48%	0.08	0.06	**0.13**
	Moving Pedestrians	-39%	-46%	0.07	0.05	0.07
	Moving Vehicles	-62%	-65%	0.03	0.01	0.03
U-District NE 42nd St (2024)	Total Devices	-27%	-16%	-0.09	**-0.09**	**-0.08**
	Staying Pedestrians	-36%	-35%	-0.10	**-0.13**	-0.02
	Moving Pedestrians	-34%	-32%	-0.14	**-0.12**	-0.02
	Moving Vehicles	-14%	-8%	0.00	-0.05	-0.05
First Ave Public Seating (2023)	Total Devices	103%	124%	**0.70**	**0.67**	-0.08
	Staying Pedestrians	92%	79%	0.34	**0.34**	0.02
	Moving Pedestrians	106%	123%	**0.38**	**0.53**	-0.24
	Moving Vehicles	100%	117%	**0.87**	**0.75**	-0.02
Taylor Ave Pickleball Court (2023)	Total Devices	-14%	-13%	n/a	-0.11	-0.04
	Staying Pedestrians	-41%	-20%	n/a	-0.15	**-0.18**
	Moving Pedestrians	-37%	-22%	n/a	-0.12	**-0.15**
	Moving Vehicles	-6%	-9%	n/a	**-0.12**	0.00

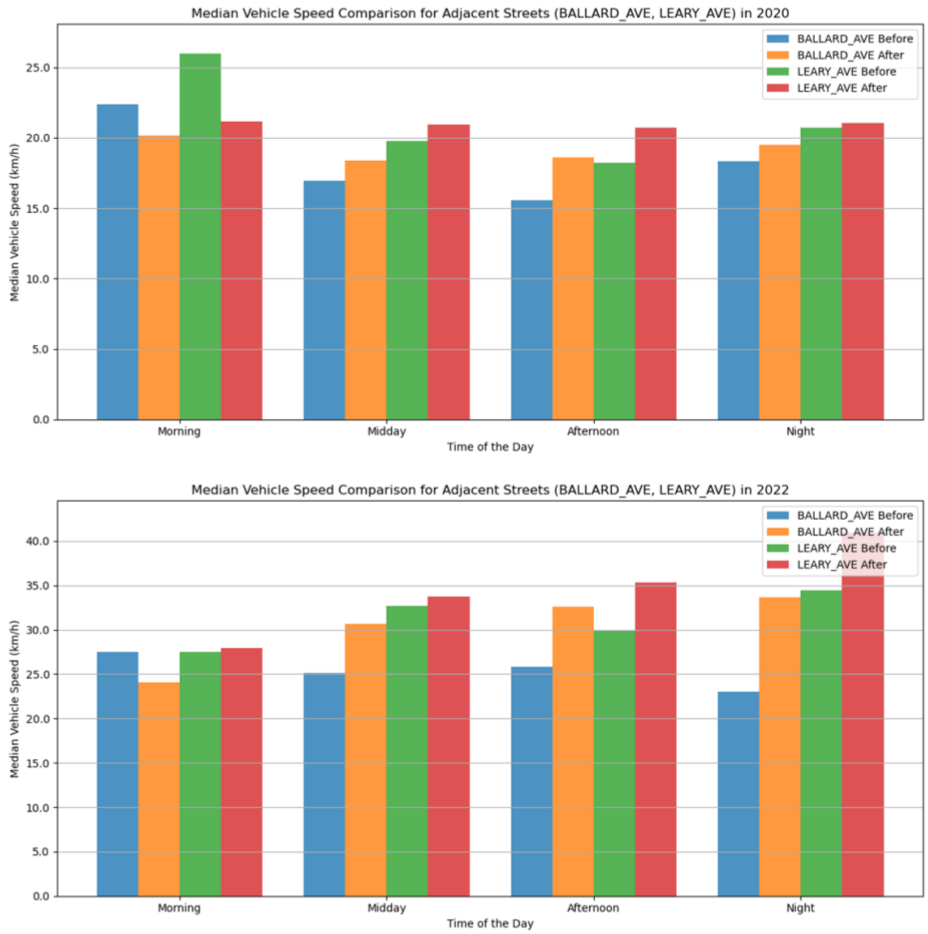

Figure 7 Vehicle Speeds on Treated Street and Adjacent Street for Ballard Ave Project

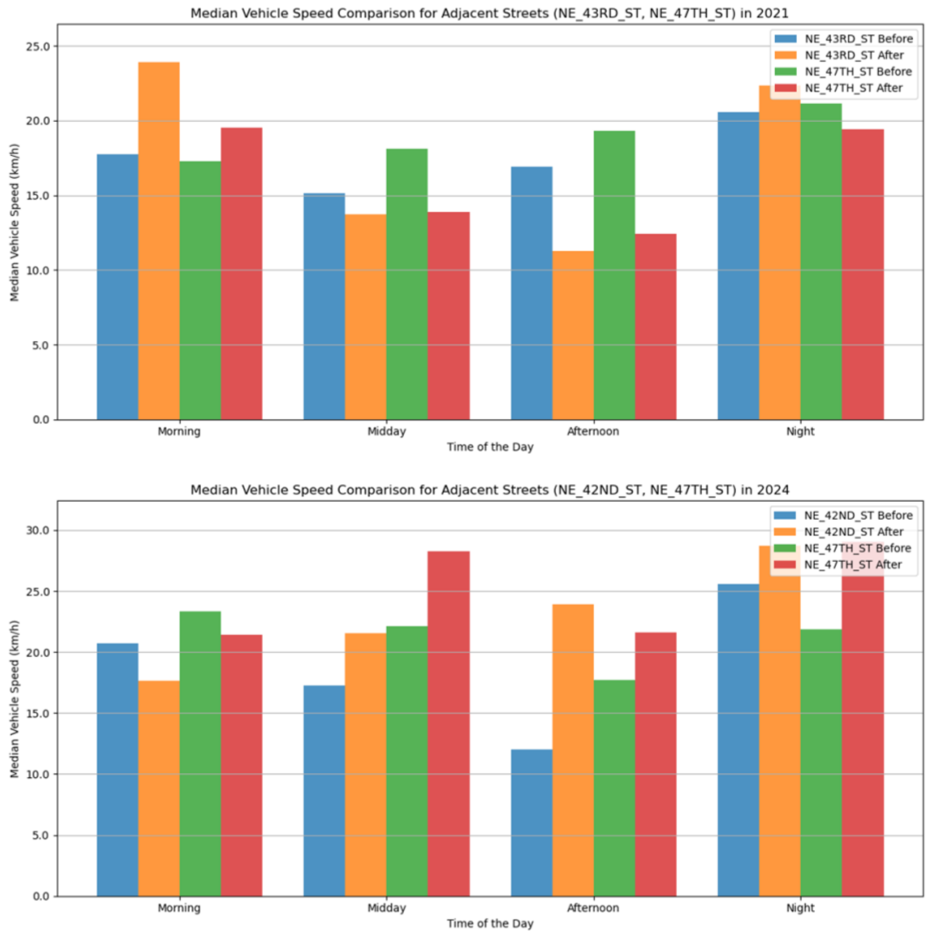

Figure 8 Vehicle Speeds on Treated Street and Adjacent Street for U-District Project

Impacts on Visit Patterns

In addition to the study of the traffic changes, we also investigate the visitor pattern shifts from the street furniture and repurposed space, including the changes in visitor count, visit dwell time, visit arrival time (time of day and day of week), and visitor origin and socio-demography distributions (e.g., home CBGs number and distance, median income and median age distribution).

As shown in Table 4, we see an increase in average weekly visits to Ballard Ave Café Street (2020) at the treated site, and for the First Ave Public Seating (2023) at both the census block group and site level. The observation is consistent with the findings from our examination of pedestrian and vehicle traffic changes. Table 4 also shows the median visit dwell time changes: visitors stayed longer after the implementation of curbside dining on Ballard Ave in 2020 and the outdoor picnic tables installed on NE 43rd St in 2021. The Taylor Ave pickleball court conversion area also sees longer visitor dwell time after the intervention. We don't observe any increase in the visitor dwell time for First Ave Public Seating, despite the fact that the number of visitors increased a lot in the area. Figure 9 shows the distribution of the visitor dwell time for the before and after periods. For Ballard Ave visitors in 2020, we see an increase in visitors staying between 1 hour and 3 hours, which is the time frame for typical restaurant dining. For Taylor Ave Public Seating, the shorter stays (within 30 minutes and between 30 minutes and 1 hour) increase a lot, indicating the area attracts more visitors for outdoor social or shopping instead of longer stays.

Figures 10 and 11 show the distribution of visitor arrival time, time of the day and day of the week respectively. Visitors to Ballard Ave after the curbside café started increase mainly during the afternoon (2pm – 6pm) and night (6pm – 10pm) hours. Ove the week, the visitors increased the most on weekends (Friday and Saturday). The pattern shift in the visitor arrival time for Ballard Ave improvements in 2022 also sees an increase during mid-day (10am – 2pm), which means there are visitors increase for other activities than dining. Visitors to the U-District area didn't show a specific trend. For example, there may be increases on weekdays and weekends. For First Ave Public Seating, we see a significant increase in visitors in the morning hours (6am – 10am) and during early weekday such as Monday and Tuesday. The likely explanation is that the area attracts more people out for social or other activities than shopping or dining. For example, enhanced aesthetic appeal and functionality on the street (public seating) encourages visitors to visit the area for socialization and strolling around the area. We also see the proportion of morning and midday and weekday visits increase for the Taylor Ave Pickleball Court area, indicating that the area might be of interest to visitors for recreational purposes instead of commercial.

We also explore the shift in where the visitors come from and the visitors' possible socio-demographic characteristics. Visitor home CBG data, shown in Table 5, reveals an increase from 281 to 373 unique home Census Block Groups (CBGs) and a median distance increase from 5.7 km to 6.6 km, suggesting a broader visitor base for Ballard Ave Café Street implementation in 2020. The median distance for visitors to the NE 43rd St outdoor café decreased (8.9 km to 3.3 km) while the median distance for visitors to the NE 42nd St summer green street fair increased (3.9 km to 9 km), suggesting that the outdoor café may attract local visitor while the summer street fair will be attractive for visitors from farther away. The number of home CBGs for visitors to the First Ave Public Seating area increased while the median distance decreased from 10.6 to 4.8 km, indicating a localized shift. The number of home CBGs for visitors to the pickleball court area decreased while the distance increased, indicating the area will probably target a special group of visitors (who are interested in pickleball and willing to travel to play).

Figures 12 and 13 show the median age and median income distribution of visitor home CBGs. We see that for Ballard Ave Café Street implementation in 2020, the peak of median age is flattening out and for improvement in 2022, we see shift from younger visitors to middle aged and older visitors. The visitors from income ranged about \$100,000 and higher income (\$250,000) increased when the curbside café opened in 2020, while the 2022 improvement attracted more visitors coming from income range in between. The U-District outdoor café (2021) attracted more visitors from younger CBGs while the street fair (2024) increased the visitors from older CBGs (60-70 years old). The home CBGs median income distribution shows a flatter pattern for both the outdoor café (2021) and street fair (2024), indicating a broader range of visitor incomes. The First Ave Public Seating shows increase of visitor from CBGs of median age 50-60 and peak at the median income of (\$70,000 - \$80,000), and the Taylor Ave Pickleball Court shows a shift of median age of 10 years older (peak at 40 years old to peak at 50 years old) and a narrower spread of median income of home CBGs (peak at income of \$80,000, while the lower and higher income both reduced). The patterns suggest the public seating and pickleball court may appeal to a specific group of visitors instead of a broader range.

Table 4 Mean Weekly Visits Changes and Median Visit Dwell Time at Census Block Group and Treated Site

Study Site	Mean Weekly Visits		Median Visit Dwell Time (minutes)			
	CBG	SITE	CBG		SITE	
	% Change	% Change	Before	After	Before	After
Ballard Ave Café Street (2020)	1.4%	37.8%	44.8	49.6	48.6	62.9
Ballard Ave Café Street (2022)	-8.2%	3.5%	67.8	70.5	72.7	71.5
U-District NE 43rd St (2021)	-37.3%	6.0%	36.5	43.6	34.7	36.7
U-District NE 42nd St (2024)	-21.0%	-34.8%	51.4	49.5	48.0	38.5
First Ave Public Seating (2023)	136.3%	116.5%	78.4	67.1	80.0	66.7
Taylor Ave Pickleball Court (2023)	-46.1%	-84.0%	49.4	55.0	62.3	79.2

Table 5 Number of Unique Home CBGs and Distance from Home CBG for Visitors to the Treated Site

Study Site	Number of Unique Home CBGs		Distance (km) from Home CBG					
			Mean		Median		Max	
	Before	After	Before	After	Before	After	Before	After
Ballard Ave Café Street (2020)	281	373	18.2	20.2	5.7	6.6	408.1	372.9
Ballard Ave Café Street (2022)	134	133	16.7	24.5	4.8	6.1	407.1	391.4
U-District NE 43rd St (2021)	44	33	15.8	11.5	8.9	3.3	85.5	92.8
U-District NE 42nd St (2024)	47	35	8.9	29.2	3.9	9	402.9	366.9
First Ave Public Seating (2023)	42	57	27.9	22.2	10.6	4.8	275.5	353.1
Taylor Ave Pickleball Court (2023)	59	19	29.2	44.4	12.1	39.7	380.3	184.4

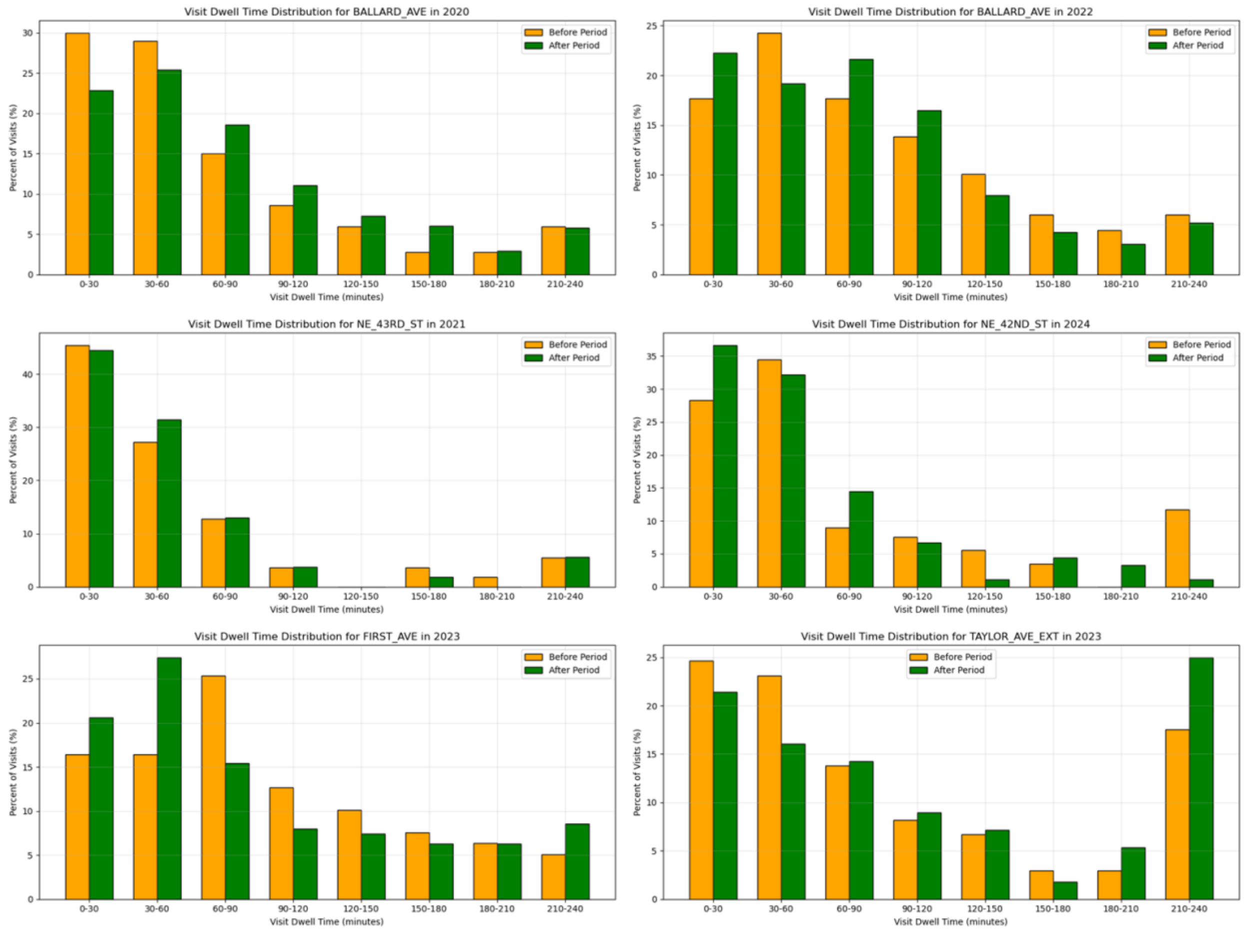

Figure 9 Visit Dwell Time Distribution Before and After Intervention

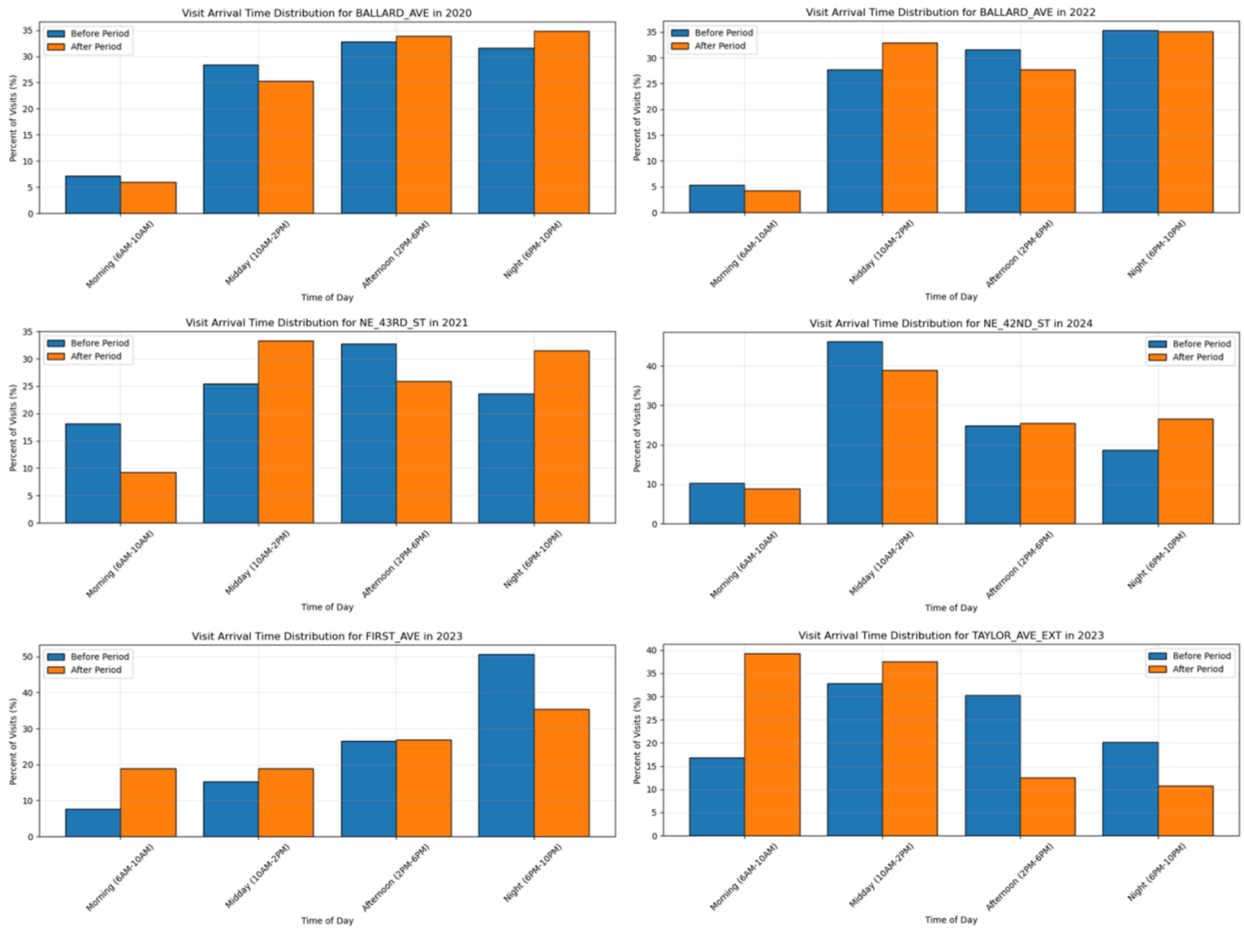

Figure 10 Visit Arrival Time of Day Distribution Before and After Intervention

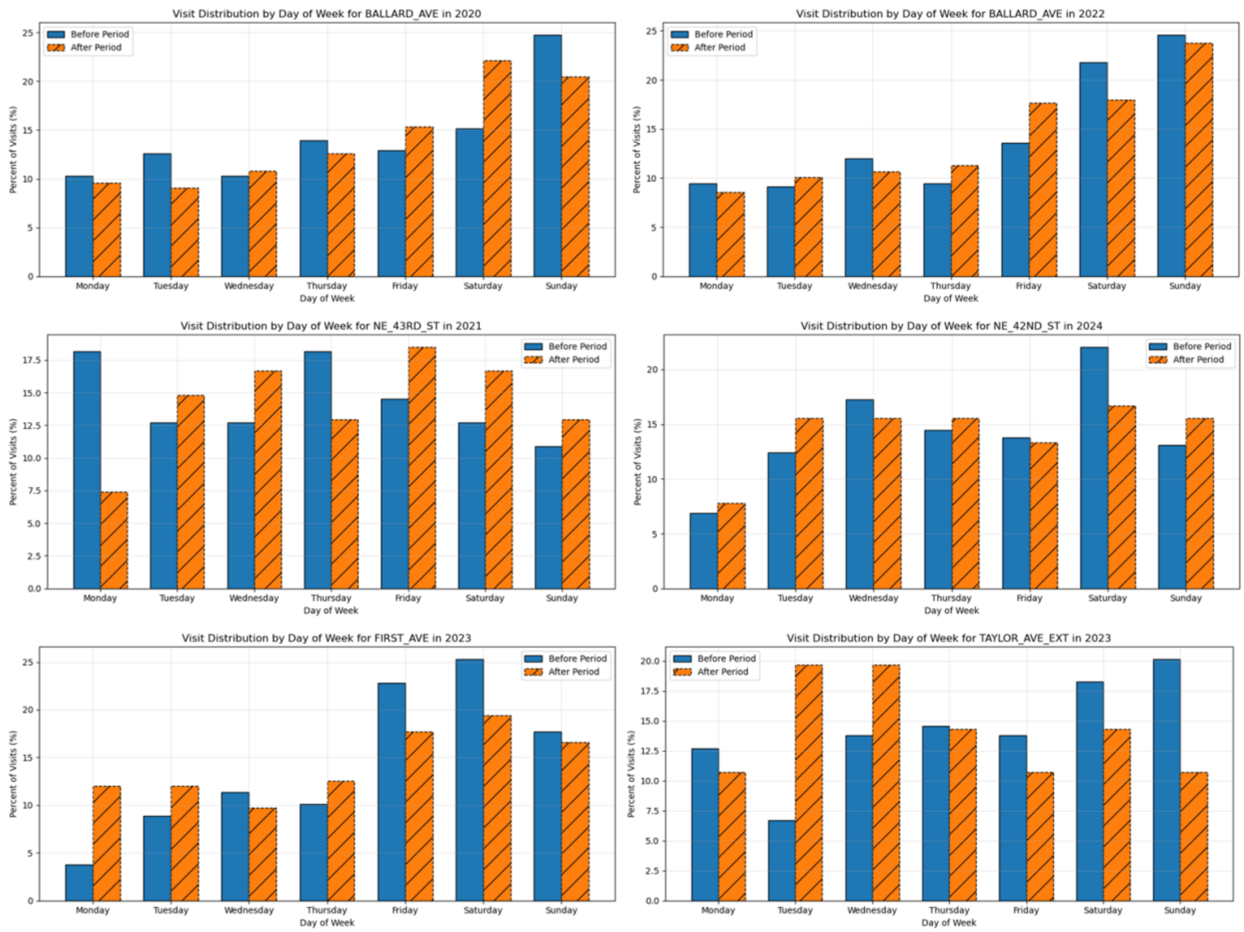

Figure 11 Visit Arrival Day of Week Distribution Before and After Intervention

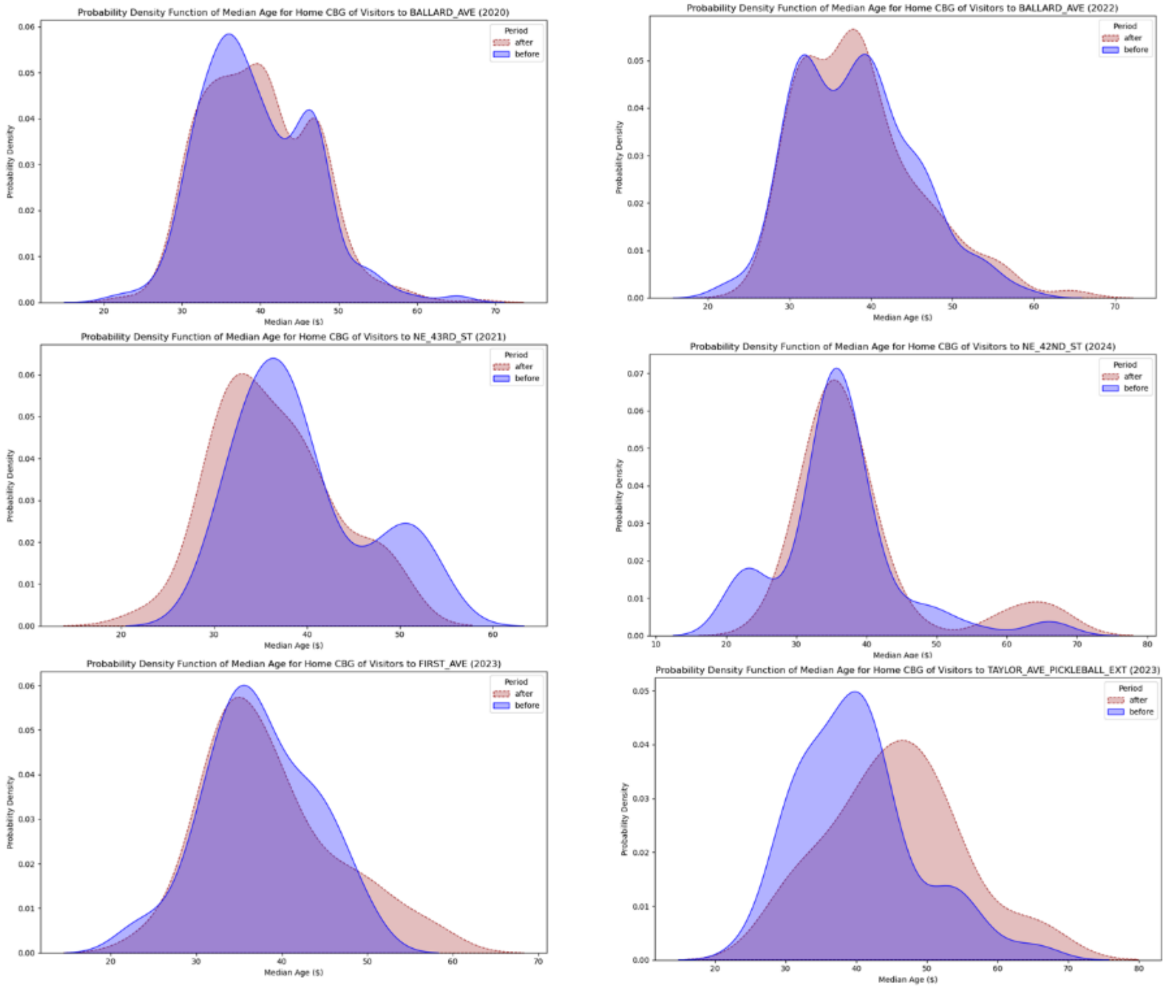

Figure 12 Visitor Home CBGs Median Age Distribution Before and After Intervention

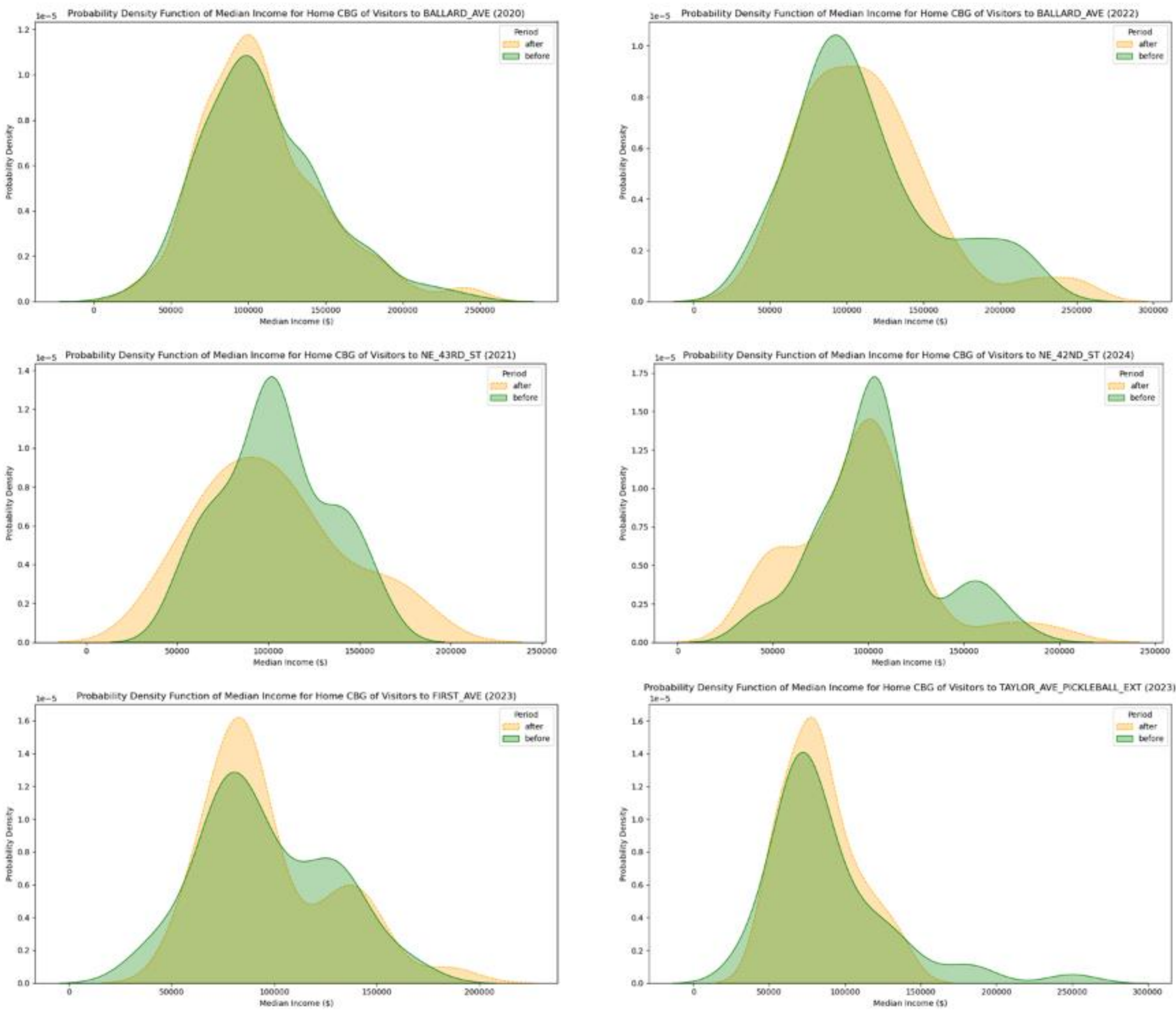

Figure 13 Visitor Home CBGs Median Income Distribution Before and After Intervention

Key Findings

- *Increased Pedestrian Activity in Outdoor Café and Seating*
  Initiatives such as Ballard Ave Café Street (2020) and First Ave Public Seating (2023) have significantly boosted the number of people staying at street level, even as overall street traffic was decreasing at the census block group level. This suggests that new public spaces like these are attracting people to hang out at the curb. And yet, Taylor Ave Pickleball Court (2023) showed no increase in foot traffic, possibly because it is such a small installation.

- *Minimal Impact on Vehicle Traffic and Speeds*
  Reconfigurations of streets like Ballard Ave (2020) and U-District (2021, 2024) had little effect on the speed of vehicles and the amount of congestion experienced on treated and adjacent roads. For instance, Ballard Ave's median vehicle speeds aligned with adjacent streets post-intervention, indicating pedestrian-focused designs do not significantly disrupt vehicular traffic.

- *Enhanced Visitor Engagement and Dwell Time*
  Ballard Ave Café Street (2020) and U-District Outdoor Café (2021) saw increased weekly visits and longer dwell times. First Ave Public Seating (2023) attracted more short-stay visitors (under 1 hour), suggesting social or recreational use, while Taylor Ave Pickleball Court also extended dwell times for specific activities.

- *Socio-Demographic Shifts Reflect Intervention Appeal*
  Ballard Ave (2020) attracted a wider, wealthier visitor base, while 2022 enhancements pulled in a middle-aged, middle-income demographic. U-District Outdoor Café (2021) raked in visitors from a younger, local-consumer base, and Green Street (2024) saw older, farther-traveling visitors. First Ave and Taylor Ave interventions catered to a niche, pulling in a middle-aged, mid-income group. They indicate very specific targeting.

CONCLUSIONS AND POLICY IMPLICATIONS

This study shows that street repurpose can boost not just foot traffic but also the type of foot traffic that's actually for local businesses, people who hang out on the street, often at cafés or in seating areas. Nonetheless, the effectiveness of designs differs by scale, context, and timing, with smaller or temporary projects facing difficulties in maintaining their impact. The findings underscore the potential of people-centered streets to boost local economies while highlighting the need for tailored designs and robust community engagement to ensure benefits.

Policy Implications

The varied outcomes across interventions suggest that street repurposing designs must be tailored to local contexts and goals. Key policy implications include:

- *Café and Seating Interventions*: curbside dining and public seating effectively increase pedestrian activity and local business revenue, especially in commercial areas. Policymakers should prioritize these designs in retail-heavy districts, ensuring sufficient space for outdoor activities and aesthetic enhancements (e.g., greenery, art) to attract diverse visitors.

- *Recreational Interventions*: The limited impact of the Taylor Ave Pickleball Court highlights challenges with small-scale or niche projects. Maximized use, especially for specialized activities such as pickleball, requires targeted marketing and more efficient integration with the overall recreational network.

- *Seasonal and Contextual Considerations*: The reduced traffic during university breaks on Green Street (2024) highlights the importance of planning that is sensitive to the timing of community activities. Temporary interventions, such as summer fairs, should coincide with the times when the community is most active. Permanent changes, in contrast, have to work for the community year-round.

- *Traffic Management*: The absence of significant congestion on adjacent streets suggests that well-thought-out reconfiguring (one-way conversions) can keep the cars flowing. Policies should include pre-intervention traffic modeling and alternative route planning to mitigate potential disruptions.

Limitations and Future Works

This study makes a significant contribution to urban planning by showing how street repurpose can affect not just the travel behavior of the street's immediate users (vehicles and pedestrians), but also the behavior of visitors and would-be visitors to that part of the city. The economic potential of café and seating interventions is highlighted in the findings, which also underscore the importance of context, scale, and timing in design success.

There are a few directions we can consider for future work. We envision a far larger and more powerful study, not only encompassing more places, but also more diverse places. And it should do so over time in a more continuous manner. Considering the methodological challenges, e.g., the LBS limitations, we can try to improve by combining LBS data with complementary sources, or find ways to incorporating qualitative and contextual data, or find methods to address the missing data and bias in LBS data.

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