Emerging Practices and Data Sources for Multimodal Transportation Planning, Design, and Performance Monitoring

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Abstract

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An increasingly multimodal transportation network and the advent of new mobility solutions means that jurisdictions should change their approaches in the planning, design, and performance monitoring of transportation systems. The work is divided into two main parts. The first section is an attempt to improve the understanding of effective multimodal transportation design processes and performance-based decision making through conducting a national-scale literature and document review. The conventional design approach of prioritizing automobiles has led to problems such as the deterioration of the environment and reduction in city quality of life. Therefore, multimodal design is becoming more widely adopted by jurisdictions through designing for multiple travel modes rather than cars only. However, as this is a relatively new field, the information available falls slightly short of the demand and there is not an ultimate source of guidance for effective multimodal design processes. This section aims to fill that gap by synthesizing "the state of the knowledge" via systematically reviewing the available academic literature, as well as "the state of the

practice" by reviewing practical documents such as state guidebooks and design manuals. For this study, multimodal will include: active transportation (e.g., pedestrians and bicycles), freight, transit, and single-occupant vehicles. The work compares the current design processes across various jurisdictions and draws conclusions on what are the best practices, data sources, and performance measures for multimodal design.

The second section of the thesis focuses on a new data-gathering tool and analysis framework that helps cities more effectively monitor the performance of micromobility services (i.e., shared e-scooters and e-bikes). As many of these services are nowadays dockless, the trips can be ended almost anywhere and not necessarily in a parking hub, which leads to these vehicles often getting mis-parked by the user, blocking sidewalks, or causing issues for people with disabilities. We developed an application for the purpose of crowdsourcing parking data from city residents to ensure that public servants get alarmed as soon as a parking infraction gets reported and to help as a long-term data solution. This tool can also be used for conducting data-driven parking audits of bikes and scooters, on a neighborhood or even a city level. We used the app to conduct two parking audits in the cities of Portland and Seattle. Summary statistics of these case studies are mentioned along with spatial analysis of the data. Several statistical models were also developed to seek for any links between parking violations and elements of the built environment and/or census tract socioeconomic factors and demographics. One of the models for the City of Seattle shows that the number of bike racks negatively correlates with the number of infractions on a census tract level. Even though the results may be biased due to low sample size, the tool itself along with the analysis piece can be used as a framework for other cities to conduct parking audits of micromobility companies.

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1 Introduction and thesis overview

We live in a world that is becoming increasingly multimodal where new mobility solutions are also gaining popularity. It is important to address the needs of every mode in the planning and design stages of a project, and to monitor the performance of various modes (including new mobility modes) on project, corridor, or network levels. To gain better multimodal outcomes from projects, engineers need clear guidance on what to do in the various phases of project development and design. It is important to have a set of steps and processes that engineers could look at and move forward with their design decision making. A review of recent literature showed that, as this is a relatively new field, there needs to be more guidance on different multimodal design processes and performance measures so that practitioners can achieve better and more clear outcomes. In other words, there needs to be more guidance in various phases of the project to answer questions such as: who the stakeholders are, how to engage with the public, what design criteria to use, what performance measures to use to evaluate projects, etc.? The first part of this thesis (Chapter 2) establishes a set of concrete guidelines by reviewing the academic literature as well as practical guidebooks and handbooks, and adopting the state of the knowledge and the best practices in this field. Multimodal design processes, level of service methods, methods for evaluating projects through performance measures, and a comparison of various jurisdictions' design processes are all reviewed. Chapter 2.2 shows the literature review and Chapter 2.3 illustrates the best practices review.

Another area where this thesis seeks to contribute is to that of performance monitoring for new mobility solutions, particularly micromobility. With micromobility vehicles (i.e., shared e-bikes and e-scooters) arriving in cities, one rising issue is that mis-parked bikes or scooters block sidewalks and pathways and interrupt or disrupt other modes such as pedestrians, particularly those with disabilities. The second part of this thesis (Chapter 3) introduces a

performance monitoring solution for micromobility parking infractions. We talk about an application that we developed which gathers crowdsourced data from city residents for reporting micromobility parking violations. The motivation behind the app along with the development is briefly described in this chapter. We also talk about different categories of parking infractions by comparing the rules for eight different cities. We then report on a case study done in the summer of 2020 where a data-driven parking audit was conducted in the cities of Seattle and Portland. Some summary statistics along with spatial analysis of the data are mentioned. We then discuss the use of publicly available data from the census and from open city portals, to model the number and severity of infractions based on different aspects of various neighborhoods including factors from the built environment (i.e., number of transit facilities and number of bike racks) and socioeconomic and demographic factors (e.g., median age, median income, minority rate, etc.). The results of the model are mentioned, and a conclusion is drawn upon in this section.

Lastly, in Chapter 4, we draw a general conclusion of both chapters to shape the understanding of how transportation planning, design, and performance monitoring can go hand in hand when preparing for a multimodal future in the era of emerging mobility solutions.

2 A review of multimodal design guidelines, processes, and performance measures

Acknowledgement: This chapter is based on a project funded by the Washington State Department of Transportation in which they aimed to establish potential changes in WSDOT's design process that would more effectively support agency staff in making decisions about the installation and design of multimodal improvements based on performance. The first phase of this project included a national scale literature review of academic papers and research reports to establish the "state of the knowledge", and the second phase included a review of federal and state guidebooks and design manuals to establish the "state of the practice". This chapter is a report on the first two phases of the project.

2.1 Introduction

In this project, we aim to assess and improve the application of multimodal performance measures and gain an understanding of multimodal design processes, to set forth a list of recommendations for WSDOT (and other state DOTs) to incorporate into their design manuals. As a first step, we are thoroughly reviewing available literature and documents in this field. The review itself can be divided into two tasks:

1) To characterize the "state of the knowledge": understand what scholarly research has been done on achieving multimodal goals in projects. We searched for research on what processes can support an effective multimodal design, and similarly, what the process is for effectively developing performance measures to assess multimodal goals. We are likewise interested in finding performance measures that have been suggested for measuring the multimodal performance of a system.

2) To get a grasp of the "state of the practice": to better understand what methods are being used by different authorities (DOTs & local jurisdictions), what multimodal performance measures they suggest, and processes that they have implemented in their project development and design phases to support successful multimodal design in practice.

The second task will be achieved through the review of jurisdiction design manuals, guidebooks, and handbooks; whereas the review for the first task is focused more on scholarly literature and research. Chapter 2.2 provides a synthesis of the literature reviewed for the first task and Chapter 2.3 synthesizes the review of the best practices for the second task.

2.2 Literature review

In this section, we review literature related to multimodal level of service and methods for evaluating projects through performance-based design and developing multimodal performance indicators. This literature review builds upon the work of previous review papers and reports including Dowling et al. (2008) and Lasley (2016) while also integrating newer studies. A guide to the materials presented in this literature review is provided in Figure 1.

First, we look at the traditional approach to transportation performance management, before turning to the recent shift towards multimodal mobility. We review some key terminology, and how the methods in the Highway Capacity Manual (HCM) have evolved over the years and look at how Levels of Service are defined for different modes. We then turn to other efforts at developing multimodal level of service (MMLOS) measures, and the development of performance measures as an important part of the design process, including the difference

between supply- and demand-based performance measures. Finally, some conclusions are synthesized based on the literature review.

The documents used for this literature review include journal articles, conference proceedings, as well as research reports. Several other state-level handbooks and design manuals were also identified during the search for literature; however, those will be discussed in more detail in subchapter 2.3, that is the synthesis of the state-of-the-practice.

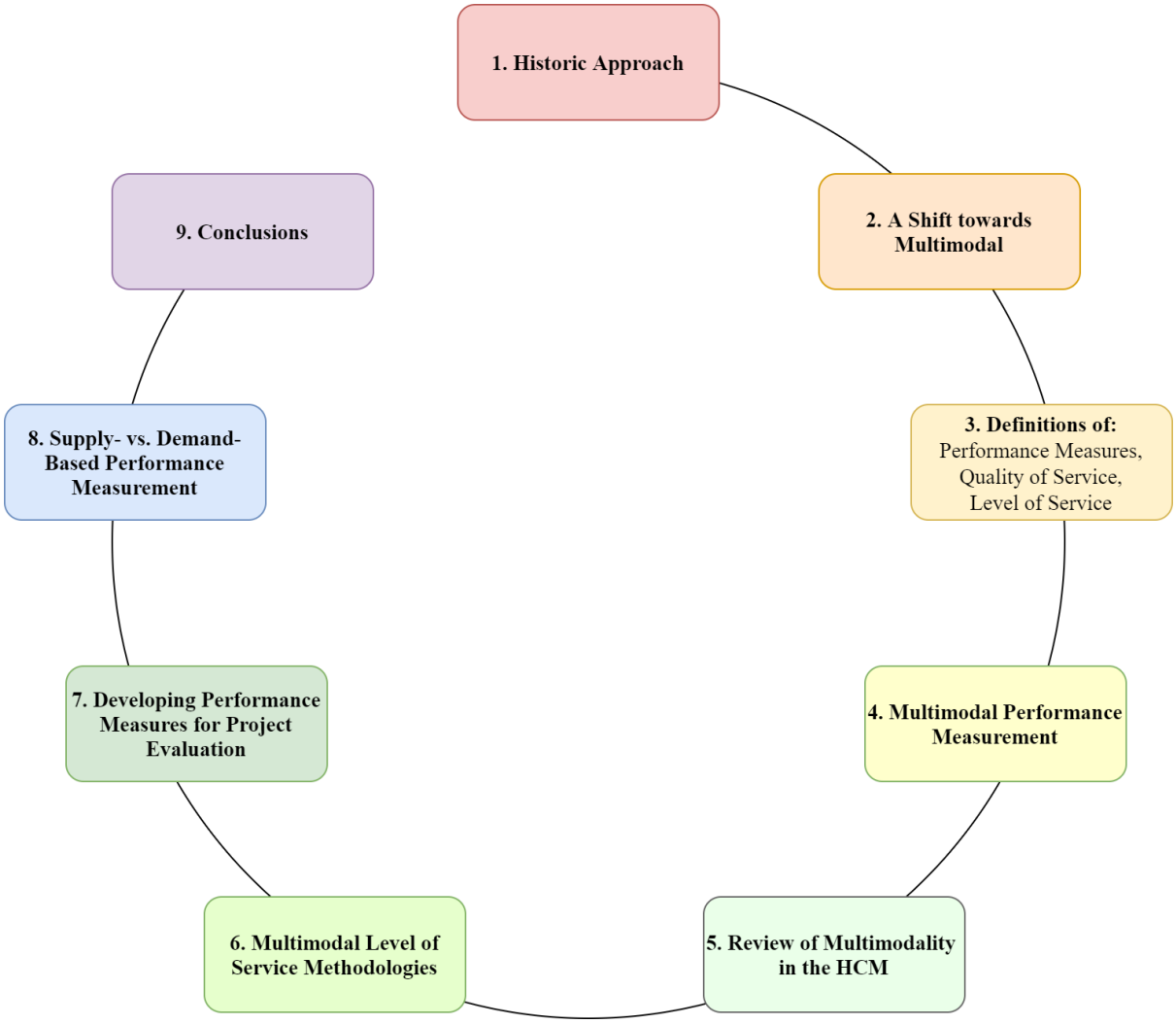

Figure 1: Literature review guide

2.2.1 Conventional approach to performance measurement

Traditionally, the Highway Capacity Manual (HCM) has been used for measuring the performance and operations of highways and other transportation network facilities. Single-mode measures such as delay and travel speed have been primarily used in the past, and are still in use among many practitioners. Furthermore, these measures were primarily established for measuring the performance of automobiles and were focused on automobile movement; as a result, they have also resulted in projects that increase speed and expand roadway capacity (Seskin et al., 2015). A recent study by Dock et al. (2017) found through interviews with peer agencies that congestion and delay measures are persistently popular among the public and policymakers.

2.2.2 A shift towards multimodal and reshaping communities

In recent years, a shift has begun in how some agencies are planning and designing their facilities and how they are distancing themselves from the traditional approach of auto-centric performance measurement. Federally, actions such as the enactment of the Intermodal Surface Transportation Act (ISTEA) of 1991 initially shifted transportation policy from building of the national highway network to integrating multimodal transportation systems (Sinclair et al., 2019). Those policy transformations were continued by other national legislation such as the Moving Ahead for Progress in the 21st Century (MAP-21) Act of 2012 (Sinclair et al., 2019). Parallel movements have also occurred outside of government, such as the National Complete Streets Coalition. This nationwide movement launched in 2004, aiming to integrate people and facilities in all dimensions of transportation networks including planning, design, construction, operation, and maintenance. According to Seskin et al. (2015), the National Complete Streets Coalition is “a non-profit, non-partisan alliance of public interest organizations and transportation professionals committed to the development

and implementation of Complete Streets policies and practices." More than 700 agencies have adopted Complete Streets policies as of 2015.

The ramifications of auto-centric design policies and their adverse effects on the transportation system and environment have led to the transitions described above. Pedestrians and bicyclists have especially felt the unfavorable effects resulting from high volumes of motorized vehicles going through urban areas faster than other modes (Sanders et al., 2010). There has been a decrease in roadway safety, walkability, and bikability, while air pollution caused by vehicle emissions has increased (Sanders et al., 2010).

Several studies have indicated that one of the toughest challenges for Departments of Transportation (DOTs) and Metropolitan Planning Organizations (MPOs) in project evaluation and decision-making is the lack of consistent and comparable multimodal performance measures over time and across geographic regions (Wang et al., 2016). This deprives professionals of a framework that measures progress towards the broad objective of multimodality (Sanders et al., 2010). State DOTs routinely use performance measures to assess transportation systems. However, since this assessment is mostly based on the traditional highway engineering perspective of prioritizing automobiles, multimodal measures have been applied in more limited contexts (Dock et al., 2017).

2.2.3 Definitions of performance measures, quality of service, and level of service

The words "quality of service", "level of service", and "performance measures" are often used interchangeably; however, caution is needed since the three sets of terms each have different meanings (Phillips et al., 2001). The first edition of the Transit Capacity and Quality of Service Manual defines the terms as follows (Kittelson & Associates, Inc. et al., 1999):

> Quality of Service: "The overall measure or perceived performance of service from the passenger's or user's point of view."

Level of Service: “LOS is a range of six designated ranges of values for a particular aspect of service, graded from “A” (best) to “F” (worst) based on a user's perception.”

Performance Measures: “A quantitative or qualitative factor used to evaluate a particular aspect of service.”

Further, “service measures” is also another term used in this context, which differs from performance measures in that it represents the passenger's or user's point of view specifically, whereas performance measures can reflect any number of points of view. Service measures should be relatively easy to measure and interpret in order to be beneficial to users. Lastly, level of service grades (A-F) are typically developed and applied to service measures. (Kittelson & Associates, Inc. et al., 1999; Phillips et al., 2001). Traditionally, however, performance measures often have been viewed as the “operator’s” point of view, and they have been more vehicle-oriented, including a variety of utilization and economic measures (Phillips et al., 2001).

Level of service remains a vital communication tool for planners and engineers to communicate the results of their technical analyses to decision-makers, elected officials, and the general public in a way that is easy to understand and interpret (Dowling et al., 2002). However, public agencies and operators should understand that it is important not to just focus on calculating an LOS range because a host of other factors may influence the quality of service, and those may not easily show themselves in an A to F classification (Kittelson & Associates, Inc. et al., 1999; Phillips et al., 2001).

2.2.4 What is multimodal performance measurement?

According to Heller (2014), transportation performance measurement is defined in the FHWA as a “strategic approach that uses system information to make investment and policy decisions to achieve national performance goals”. The word "multimodal" is seen

increasingly in the literature; however, different people may use the term in different ways and to represent different concepts (Sinclair et al., 2019). The performance of a multimodal system can be expressed through measurement initiatives such as multimodal accessibility (focusing on the ability to reach destinations), multimodal connectivity (quantifying the cohesiveness of travel across modes), or multimodal productivity (the productivity of actual person trips made across the network through all modes) (Sinclair et al., 2019).

Lasley (2016) argues that there are two main approaches to multimodal performance measurement: (1) "a collection of single-mode measures bound in a single resource"; or (2) "a single resource/measure that examines multiple modes simultaneously using a common comparison factor". Often times, multimodal performance measures are developed for estimating progress towards a broader goal. However, there is no single broad goal for multimodal performance measures since effective multimodal performance measurement should include metrics that examine a variety of goals, e.g., system quantity, effectiveness, efficiency (delay), connectivity, competitiveness, and safety (Lasley, 2016).

Lasley (2016) further examines recent relevant literature, providing a common level of understanding and recommended steps to create useful multimodal performance measures. The paper concludes that measures that examine network performance among and between multiple modes are rare. Furthermore, Kanafani et al. (2010) and Cambridge Systematics (2010) also mention that there is a need for measures that use a common denominator (e.g., delay, travel time, etc.) to allow the evaluation of the system and compare one mode against the others to match the mode and route decisions.

Another description by Seskin et al. (2015) states that performance measures can generally be interpreted to mean the data inputs that are needed when:

- Tackling long-term planning efforts;

- Selecting projects to fund;
- Performing an alternatives analyses (evaluating all feasible options for a project);
- "Considering specific elements when finalizing a project's design";
- Displaying the present state of a system using tools such as a dashboard; and Most importantly,
- "Evaluating the outcomes of a built project"

According to Seskin et al. (2015), performance measurement is the process of "establishing performance targets, modeling impacts, and monitoring results". They point out that simple before-and-after analyses may demonstrate how well a project achieved its intended goals for elected leaders and residents. However, for transportation planners, designers, and engineers, such measurement provides an additional benefit: "measuring the actual results of projects allows them to make better-informed choices for future projects.

Furthermore, the scale of analysis matters when trying to apply the right performance measures. Seskin et al. (2015) recommend that measures should be chosen thoughtfully and with consideration of scale to avoid misinformation in decision-making and evaluating results. For example, measuring vehicular LOS at only one intersection may lead the planner or engineer to conclude that a wider intersection is needed, which may unintentionally cause bottlenecks elsewhere on the corridor. Such inattention to scale will potentially reduce safety and quality of the environment for individuals using other modes such as walking or bicycling in a nearby intersection. On the contrary, if a particular segment is not yet connected to a larger walking and bicycling network, perhaps doing a before-and-after measure of the number of people walking or bicycling only on that street segment may be misleading as the broader network level may be overlooked. Heller (2014) reinforces the notion that scope and scale are important when considering performance measures, since

metrics can be applied at an entire transportation system level, a corridor level, or even a facility level.

2.2.5 Review of multimodality in the Highway Capacity Manual (HCM)

2.2.5.1 HCM 1985

At the time of HCM 1985, the auto-centric design approach was at its peak, but there were still some methods available for pedestrian and bicycle modes in the Highway Capacity Manual. According to Phillips et al. (2001), HCM 1985 offered very limited scope for the pedestrian and bicycle modes, and defined performance measures for the environments of these two modes plainly as the degree of discomfort to the user due to overcrowding of the facilities. The applicability of this sort of measure is extremely limited and is not suitable for understanding the performance of those modes. Furthermore, multimodality was not mentioned at that time in the HCM.

2.2.5.2 HCM 2000

HCM 2000, in addition to methods for automobile LOS, contained significant new methods for analyzing pedestrian and bicycle LOS while also including a summary of the TCQSM for transit analyses (Dowling et al., 2002). However, somewhat similar to the methods provided in HCM 1985, these new methods use sidewalk and bicycle lane capacity for measuring pedestrian and bicycle level of service and neglect the impacts of facility design and the interaction of those modes with vehicular traffic on peoples' perceived level of service. Such design features have a real influence on pedestrian and bicyclist satisfaction with a facility and consequently its quality of service (Dowling et al., 2002).

For transit, however, due to the publication of the Transit Capacity and Quality of Service Manual (TCQSM) (Kittelson & Associates, Inc. et al., 1999), several methods, performance measures, and LOS measures were made available that took the perspective of transit riders

into account. These LOS measures were provided for transit systems, transit route segments, as well as transit stops (Dowling et al., 2002).

2.2.5.3 HCM 2010

2010 was the year that multimodal design was highlighted in the manual. A study by Elefteriadou et al. (2015) summarizes the multimodal aspects of HCM 2010. Their study covers three different methods presented in the HCM for: (1) uninterrupted-flow facilities (Chapter 15); (2) interrupted-flow facilities or urban streets (Chapters 16-18); and (3) off-street pedestrian and bicycle facilities (Chapter 23). All are discussed below to understand the HCM's approach to multimodality.

(1) Uninterrupted flow

Uninterrupted flow refers to facilities where traffic is not controlled by traffic signals, stop signs, or yield signs. A method for evaluating bicycle operations on multi-lane and two-lane highways is provided in the manual. A bicycle LOS (BLOS) score scaled from A to F is reported which represents "the quality of service for the bicycle mode when it is traveling along the highway within the same right of way as other motorized vehicles." It is assumed that bicyclists always use the rightmost lane of the highway (or shoulder when available). The factors that the BLOS score is sensitive to are: "the vehicular demand in the rightmost lane of the highway, the width of that lane, the width of the shoulder, percentage of heavy vehicles, the speed limit of the facility, presence of parking, and pavement surface condition" (Elefteriadou et al., 2015).

(2) Interrupted flow

HCM 2010 provides LOS calculation procedures for on-street transit, bicycles, and pedestrians on urban streets. The manual uses multiple performance measures in determining LOS, rather than the more-traditional single-measure approach (e.g., speed, delay, density).

Transit analysis for urban street facilities and segments

Transit LOS measures are provided in the HCM for evaluating on-street public transit service in a multimodal context. On-street transit service comes in contrast to off-street service which refers to transit in its own right of way (e.g., a transit lane) or transit that travels along a street without stopping to serve passengers (e.g., express bus). The Transit Capacity and Quality of Service Manual (TCQSM) provides more performance measures, computational methods, and spreadsheet tools for evaluating capacity, speed, reliability, and quality of service of both on- and off-street transit services. The method provided in the HCM simply provides a 6-scale grade of A to F and is sensitive to the following: the frequency of on-street transit service, perceived bus speed (includes variables like on-board crowding, reliability, and other factors), and the quality of the pedestrian and waiting environments at bus stops.

Bicycle analysis for urban street facilities, segments, and intersections

The HCM provides BLOS for various scales and facilities, namely signalized intersections, links (between intersections), segments (links plus intersections), facilities (multiple consecutive segments), and off-street bicycle and shared-use paths/trails. The signalized intersection BLOS - stratified as usual into LOS A to F - is sensitive to the following variables: “lateral distance between the bicyclist and traffic, volume of traffic in the right lane, percent of heavy vehicles, presence of on-street parking, and cross-street width" (Elefteriadou et al., 2015). Bicycle speeds and volumes, and signal delay for the bicycles are not factored in the bicycle LOS. No methods are provided for BLOS for unsignalized intersections including roundabouts, due to lack of research.

BLOS is also calculated for links, which is sensitive to all the variables mentioned above (except the width of cross-street since it is inspecting links and not intersections) in addition to the following variables: the speed of traffic, the number of unsignalized access points, and pavement conditions. Finally, for BLOS of urban street segments, a weighted combination of the signalized intersection and link LOS values is used, and for the facility LOS, a weighted average of the segment LOS values is utilized.

Pedestrian analysis for urban streets and intersections

Pedestrian LOS (PLOS) is also performed for the same geographic types/levels as for the bicycle analysis. In addition to those levels, "street corner pedestrian storage and crosswalk circulating capacity checks for pedestrians" are also provided in the HCM at a signalized intersection. The PLOS methods provided in the HCM do not take into account ADA accessibility; a separate assessment should be performed by the analyst to incorporate that when evaluating the overall quality of service.

The PLOS at a signalized intersection is sensitive to: "pedestrian delay due to the signal, lateral distance between the pedestrian and traffic, the volumes of traffic in the right lane, the left and right turning volumes crossing the crosswalk while pedestrians have the *walk* indication on, the percent of heavy vehicles, and the presence of on-street parking" (Elefteriadou et al., 2015). PLOS also depends on the number of lanes on the cross-street as well as the number of right turn channelization islands that the pedestrian has to cross.

Finally, the PLOS at the link level is sensitive to "the lateral and buffer separation between pedestrians and traffic, the traffic volume in the right hand lane, the percent of heavy vehicles, the speed of traffic, the presence of on-street parking and barriers such as street trees, and the difficulty of making mid-block crossings (where legal)" (Elefteriadou et al., 2015). Moreover, a density-based pedestrian LOS is calculated for sidewalks with high

pedestrian volumes, and the lower of the two LOS values is reported as the link LOS. Segment LOS, similar to that of the bicycle analysis, gets calculated through a weighted combination of the signalized intersection and non-density link LOS values; but, it is also compared with the density-based link LOS and the worse is selected. Finally, facility LOS is a weighted average of the segment LOS values.

(3) Off-street pedestrian and bicycle analysis

Methods are also provided in the HCM for analyzing off-street pedestrian and bicycle facilities where three situations are considered: (1) a pedestrian only facility (e.g., stair, pathway, etc.) where LOS is estimated by the available space for the average pedestrian; (2) a pedestrian LOS on a shared-use path, where LOS is estimated by the number of times and average pedestrian meets or is passed by bicyclists; and (3) bicycle LOS on a shared-use path, determined by the number of times the average adult bicyclists meets, passes, or is passed by other path-users.

As a conclusion, it is important to point that the HCM analysis provides performance measures from a traffic operational quality viewpoint, and its provided methods estimate performance measures particularly related to that aspect of transportation. Elefteriadou et al. (2015) conclude that for comprehensive planning purposes, a wider set of performance measures are needed that consider other aspects beyond that of traffic operational analyses, such as environmental and financial measures.

2.2.5.4 HCM 6th Edition

Elefteriadou (2016) provides a brief introduction to the 6th edition of the Highway Capacity Manual. This latest edition of the manual is subtitled "A Guide for Multimodal Mobility Analysis," pointing to the shift in perspective toward multimodal analysis. The manual

incorporates latest research findings into an extensive set of analysis tools for the operational analysis of traffic.

Elefteriadou (2016) categorized four dimensions mentioned in the scope of the HCM6, namely: capacity, quality of travel, quantity of travel, and accessibility. The HCM6 still mainly focuses on evaluating the capacity and quality of service of facilities and modes through data related to quantity, especially demand, as an input. They provide LOS as one of the best-known measures for assessing the service of a facility; however, "they also provide tools for estimating additional performance measures for a variety of modes and facilities." (Elefteriadou, 2016) Elefteriadou (2016) also clarifies that LOS measures are intended to communicate about the operations of a facility to a non-technical audience and that performance measures recommended in the HCM6 can be used by themselves without the use of LOS.

Two new automobile-related chapters have been added to the manual, listed in Elefteriadou (2016), including Chapter 11, Freeway Reliability Analysis and Chapter 17, Urban Street Reliability and Active Traffic and Demand management. The focus of these new chapters seem to be evaluating travel time reliability through the distribution of travel times, over a broad period of time (e.g., a year) (Elefteriadou, 2016), and they do not seem to be involving multimodal context into them. But, the study also mentions that "in response to the increasing need to estimate the performance measures for pedestrian, bicycle, and transit facilities, as well as the interactions with vehicles", the HCM has provided certain methods for those assessments namely, Chapters 16 through 23 (methods for assessing non-automobile modes and their interactions with vehicles) and Chapter 24 (off-street pedestrian and transit facilities). Chapter 15 of the manual evaluates bicycle operations on highways (multi-lane and two-lane) with the addition of information from a newer research. The manual still

recommends to use TCQSM for the evaluation of transit facilities; however it does consider the effects of transit along urban streets within a "multimodal analysis framework" (Elefteriadou, 2016).

In summary, there have been some additions to the HCM6 as compared to HCM 2010; but there does not seem to be a radical change in how HCM is calculating performance of facilities.

2.2.6 Multimodal Level of Service: old and recent methods

In the late 1990s, some studies started addressing multimodality and the need for multimodal performance measures in pursuit of the ISTEA legislation, and the Florida Department of Transportation (FDOT) was one of the earliest funders of research in this area. Guttenplan et al. (2001) was probably one of the first papers to study multimodal level of service analysis at the planning level. The research focused on methods for determining the level of service (LOS) to pedestrians, bicyclists, scheduled fixed-route bus users, and through vehicles on arterials. It is based on work by FDOT, which had developed a multimodal LOS analysis process to measure and provide mobility for diverse roadway users.

In another project, FDOT entered into a contract with the University of Florida and two consulting firms that were the leaders of research in quality and level of service methodology development at the time, to address the need for a planning level and quality of service analysis for Florida (Phillips et al., 2001). Some of the objectives of the project (which were shaped in the summer of 1998) were to: (1) perform a national literature review of multimodal level of service methodologies to implement the best possible methodology in Florida; (2) measure the performance of corridor segments in two districts by applying and validating Bicycle LOS and Roadside Pedestrian Condition techniques; and (3) apply and test new HCM performance measures for transit (in test districts).

The study further shows that there were some concerns across local governments, questioning if statewide requirements will shift to standardizing and requiring use of multimodal performance methods (Phillips et al., 2001). However, the focus at that time appeared to be on developing techniques, not standardization, and to enable and support "local government efforts for multimodal planning by offering professionally acceptable techniques." They suggest several performance measures in the report and offer a literature review of processes used up until that point (being now somewhat outdated, it is not included in this study).

In addition, Dowling et al. (2002) developed and tested a method that measured the user-perceived quality of service from a multimodal perspective. The study also asserted that in the HCM 2000 release, there was a shift towards analyzing automobiles and transit in the same corridor for the first time; but, it indicated that there were not any efforts to compile the auto and transit levels of service into an aggregate measure for corridor-level assessment.

The proposed methods in Dowling et al. (2002) estimate automobile and transit LOS analyses based on the HCM 2000 and TCQSM, respectively, while calculating bicycle and pedestrian levels of service based on models developed by the researchers. Four classes of corridors are recommended, and the methods were tested on two classes of urban corridors, with and without a freeway.

In more recent years, several multimodal level of service methods have become available throughout the literature. One study used eight different MMLOS methods for an arterial corridor section case study in Austin, Texas (Zuniga-Garcia et al., 2018). Zuniga-Garcia et al. (2018) list the following methods:

1) Highway Capacity Manual;

2) Transit Capacity and Quality of Service Manual;

3) Charlotte, NC, Urban Street Design Guidelines (USDG);

4) pedestrian and bicycle environmental quality indices (PEQI and BEQI);

5) assessment of level of traffic stress (LTS);

6) bicycle compatibility index (BCI);

7) deficiency index (DI); and

8) Walk Score, Bike Score, and Transit Score

The study is focused on evaluating pedestrian, bicycle, and transit modes in particular, and comparing letter-metric grades (e.g., HCM and TCQSM) with the use of different score measures (e.g., BCI, WalkScore, etc.).

Their major findings are that although the HCM MMLOS assessment is suitable, it requires user training and significant data. Furthermore, TCQSM can be used hand in hand with HCM to complement the transit mode for corridor evaluation. The authors also indicate certain strengths and weaknesses of different approaches, for instance USDG being appropriate for intersection analysis but not for corridor evaluation, and PEQI and BEQI being appropriate for corridor analysis but not sufficient for robust intersection evaluation. They finally indicate that they recommend applying the HCM and TCQSM methods to assess multimodal performance in corridors. Also, they assert that there is still not an overall MMLOS that includes multiple modes by any of the methods, and the way all these methods work is that the analysis should be applied separately for each mode. Besides, an aggregation of the results to provide an overall score requires knowledge and judgment of how to weight different modes, making the aggregated mode results subjective and biased (Zuniga-Garcia et al., 2018).

While several MMLOS methods are available in the literature, efforts for developing heuristic methods have also been seen. Ni et al. (2013) proposed a new evaluation method that captures both the efficiency and safety of all road users at the same time in one level of service metric. MMLOS is used for evaluating delay (using methodologies similar to that of Dowling et al. (2008)), and a multimodal safety level of service (MSLOS) is established for evaluating safety through conflict checks at the intersection. They are both ranked 1 to 6. The multimodal comprehensive level of service (MCLOS), is established, and a case study of a typical intersection in the VISSIM-SSAM simulation platform assesses the method.

The work of Sinclair et al. (2019) focused on developing performance measures that help assess the performance of a multimodal design project (e.g., an intersection, a street, etc.), also known as facility-based performance measurement. The research discusses a Multimodal System Productivity (MSP) score, which is the number of completed person trips per network minute. This research is referring to "multimodal trips" in a network-level and trip-based context (i.e., trips that use different modes along their path). This measure is defined based on the definition of productivity: "the ratio of input to outputs in the production process". For multimodal transportation systems, completed person trips are production output and network travel times are production inputs; therefore, the MSP score is the number of completed person trips per network minute.

Kanafani et al.(2010) identified the attributes that affect multimodal performance from the demand and supply perspectives, and their roles in multimodal transportation. The research offers a utility-theory-based analytical framework leading to the construction of an indirect utility function that quantifies the user's perception of level of service for multimodal alternatives. A set of metrics were also developed to quantify the measures of performance from the supplier's standpoint. This work seems to emphasize the intermodal integration of

various modes (using an entire trip that consists of several links of different modes) rather than focusing on what metrics can individually be used to measure the performance of each mode for a certain project. Their utility function is based on the following factors for the user's perspective: Time (access, waiting, in-vehicle traveling, transfer), money (out of pocket, indirect, bundle), safety, reliability, and flexibility (Kanafani et al., 2010). The first two are disaggregate factors (meaning that they vary for each mode-link of the entire trip) whereas the latter three are aggregate factors (meaning that if even one of the mode links of that entire trip is unsafe, unreliable, or inflexible, the user may disregard that entire multimodal bundle as a whole). They also apply a utility function for the supplier's side, which is broken down into the government's perception (issues of concern are equity, energy, emission, monetary cost, and level of service) and the agency's perspective (factors are cost, revenue, and subsidy).

2.2.7 Developing performance measures for project evaluation

There have been various studies in the pursuit of a true multimodal performance indicator, but there have not been promising results. Sinclair et al. (2019) recently sought to conduct a literature review to find an “ideal” multimodal system performance measure. They reported conducting a detailed literature search and concluded that they did not find an “ideal” multimodal transportation performance measure in their literature review, although the details of their search were not mentioned in the report. They therefore developed their own measure called Multimodal System Productivity (MSP).

Harvey et al. (2018) discuss the performance measure development process of a project by arguing that many design guidelines provided by federal or high-level agencies differ in terms of context with what is needed in a particular community. In other words, each agency may have to develop context-specific design guidelines for their own use rather than directly

applying national or state-level guidelines. For instance, national or state design guidelines may not be applicable or provide guidance on every design aspect of a complete street project at a local level. Therefore, regardless of such design guidance being provided at various higher levels, local agencies have to take action and develop their own "complete street design guidelines". If a region does not have complete street design guidelines for its locality, Harvey et al. (2018) suggest that they determine their community needs and preferences while examining existing street typologies, climate, and current and planned transport modes. The study further anticipates that in the future, with more data collection, analyses, and information documentation being readily available, complete street design guidelines will likely change in consideration of what has and has not worked (Harvey et al., 2018).

There have been similar guidelines offered in the literature regarding project evaluation through the development of objectives and performance measures. A study recommended four general steps for agencies when undertaking project evaluation (Seskin et al., 2015):

1. **Agree to goals and objectives of the project**: the goals of the project need to be established and agreed upon. This can be a challenging process since different needs are expressed by residents, elected officials, and transportation leaders. However, challenges can be overcome by encouraging participation and engagement in dialogue leading to consensus and mutual understanding. Furthermore, certain goals may exist on a network-level rather than a project-level. For example, a project by itself may not achieve many goals for a particular street segment, but any contributions to a broader goal, when viewed in the context of an entire funding program or the entire network, should be considered (e.g., there may be a citywide goal to build a certain amount of accessible curb ramps each year).

2. **Determine the best ways to measure goals**: This step is to figure out which data will bring about success. Asking community members about what they will want to know

about the project once completed is beneficial when setting up data-collection practices. It is also recommended to explore alternative data sources as significant data collected by agencies other than the transportation agency may be available (e.g., sales data from business improvement districts, crash data from local police departments and hospitals, etc.)

3. **Implement measures**: Baseline data should be collected at this time for each measure, and an appropriate timeframe for evaluation after completion should be established. One best practice is to measure conditions a year before, a year after, and three years after the project is completed. Continuous data collection may be needed for some measures. Notably, not all measures need to be quantitative, and qualitative ones may be more relevant in some cases (e.g., collecting quotes from people's experiences with the street and what they like about it, either collected in the project outreach or through additional interviews after completion).

4. **Share results**: Sharing results with the public is an even more powerful tool than project evaluation by itself since it allows members of the public, elected officials, and other partner government agencies to understand results. It is important to design and package an attractive final product. Photos should be included, accompanied by quotes regarding the project

Seskin et al. (2015) underscore that data can help make better decisions when developing performance measures to suit the goals of a project, but it is not a substitute for community vision. Furthermore, another recommendation is that performance measures do not have to be complicated and sophisticated mathematical models; they can be as simple as “blocks of sidewalk added” or “number of trees planted”.

Seskin et al. (2015) outline useful performance measures for seven common complete streets goals, namely access, economy, environment, place, safety, equity, and public health. The

focus of these goals is on project-level evaluation, but some related network-level measures are also included. The report further provides a very long list of performance metrics, which we suggest that practitioners look at. The performance measures are separated by goal, mode, and scale across seven tables in that document.

Lasley (2016) further agrees with previous research that agencies should consider asking several questions that impact a multimodal performance measure before creating or deciding on using that metric. These questions include:

1) "How will the measure be used?
2) What are the ultimate goals of measurement?
3) What exactly is being measured and does this match planning objectives?
4) Is each mode treated fairly within the measure?
5) Are both people and goods considered;
6) What are the likely and worst-case impacts of the use of the measure? and
7) Who is the audience and could they understand the measure?"

Furthermore, agencies should also examine which factors are already being measured well, and which factors could use improvement (Lasley, 2016). Multimodal performance measurement generally measures either one of six factors: 1- Quantity (volume/tonnage); 2- effectiveness (throughput, such as person or vehicle throughput per hour or other similar measures); 3- Efficiency (travel time or delay); 4- Competitiveness (reliability or cost); 5- Connectivity (LOS measures or connectivity to other modes and/or facilities); and 6- Safety. These share similar terms with those mentioned in (Elefteriadou et al., 2012).

The study further recommends that in developing performance measures, it is important to make sure that highlighting one mode does not come at the cost of penalizing another (Lasley, 2016). Moreover, agencies should consider performance measures that are easily understandable and interpretable. The measures should not be too complicated to communicate and perceive. Finally, agencies should set an expectation or expected outcome for each mode. Similar to how roadways are classified in a different manner, expectations for the travel speed we get from a freeway should be different than that of an urban arterial. We should not expect the same standards across different modes (e.g., when comparing auto delay to transit delay).

Elefteriadou et al. (2012) developed a framework to help agencies in selecting a set of useful performance measures, consistent with their overall goals and quality of life desired by their community. The implementation of this framework is in the following three steps:

1) Identifying goals and objectives for the project and the transportation system of the region (e.g., reduce congestion, increase non-SOV travel, minimize environmental impact, enhance safety);

2) select a set of measures appropriate for each goal from an extensive list of measures (this list is available in Appendix A of Elefteriadou et al. (2012)); and

3) use evaluation criteria to assess each measure in light of the agency's goals, policies, and resources.

Five mobility dimensions are identified: Measures of infrastructure and environment; measure of demand and system utilization; measure of user perceptions; measure of safety; and measure of sustainability (Elefteriadou et al., 2012), and are further categorized into several subdimensions shown in Figure 2. For each of the subdimensions, an extensive list of

performance measures is identified in Appendix A of Elefteriadou et al. (2012). These performance measures are not brought in this document as it spans 22 tables; we refer practitioners to look at this important reference to identify their needed performance measures.

Furthermore, there are seven broad mobility-related planning objectives included in their study, which are then linked to the performance measures (for further information, refer to Table B.2 of their report which provides performance measures by objectives and characteristics). The planning objectives are: (1) Minimize ecological impact; (2) increase accessibility; (3) increase non-SOV travel; (4) reduce congestion; (5) optimize freight movement; (6) enhance safety; and (7) reduce air pollution. Finally, data requirements which are needed for each indicator are assessed in the study, and are available in Appendix C of Elefteriadou et al. (2012). Their study is probably one of the most useful pieces of literature found in our review, and we therefore recommend that practitioners study it further and apply their suggestions when implementing performance-based design (Elefteriadou et al., 2012).

Dock et al. (2017) state the importance of visualization tools for agencies to display how they are addressing multimodal mobility. The study provides a set of measures and a data visualization component for the District of Columbia DOT and for other agencies to use. The performance measures include a set of commute-related metrics and are shown in Figure 3 based on their modal perspective and broad mobility category.

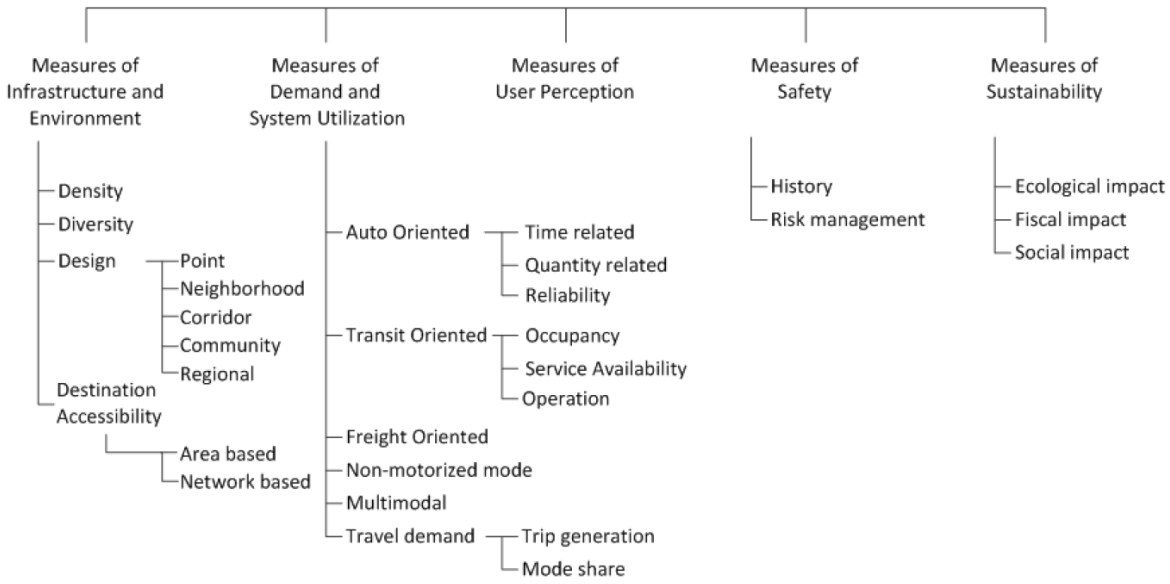

Figure 2: Classification of performance measures by mobility dimension (Elefteriadou et al., 2012)

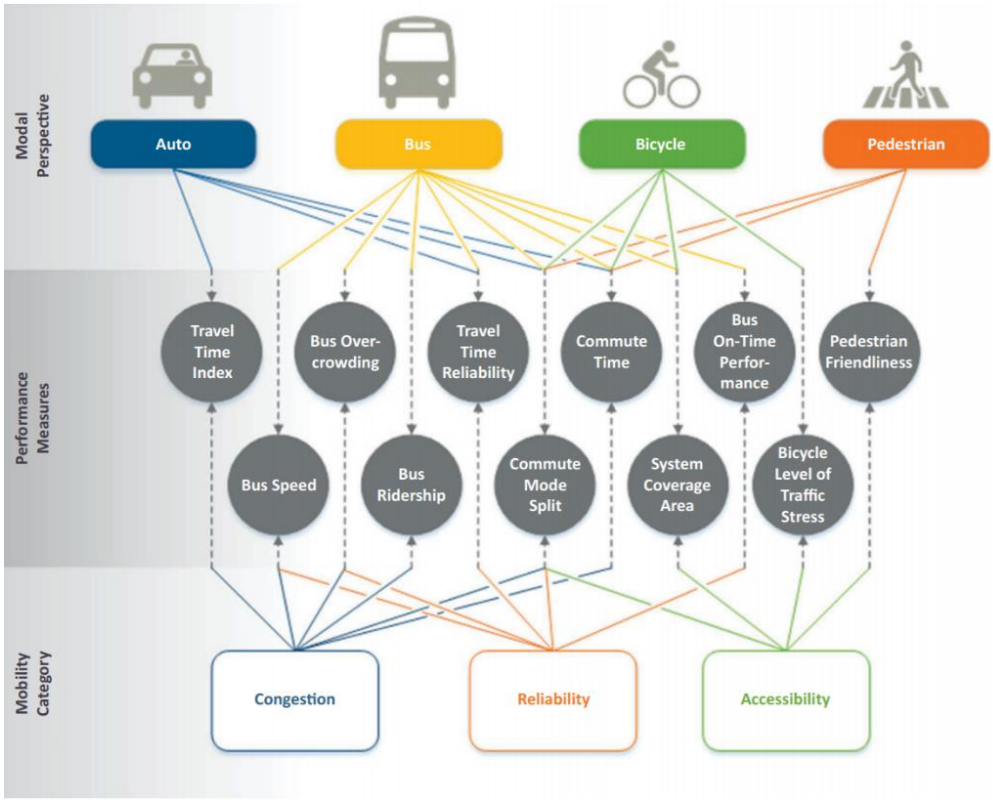

Figure 3: Performance measures by modal perspective and mobility category (Dock et al., 2017)

The study highlights that "Washington State and Florida are leaders among states in performance measurement" and that both of these states use congestion measures that address multiple modes (Dock et al., 2017). The study specifically cites the Washington State DOT's Corridor Capacity Report, a web tool that evolved out of the Grey Notebook performance publication (Washington State Department of Transportation, 2014). Congestion on major Interstate corridors is described in The Corridor Capacity Report in terms of daily vehicle delay; vehicle throughput; length and duration of routine congestion; and transit, park-and-ride, and high-occupancy vehicle lane usage. Dock et al. (2017) conclude that this shift helps the department consider its performance "through the lens of economic productivity".

Similarly, the Florida DOT produces the Multimodal Mobility Performance Measures Source Book, an annual report of mobility performance measures (Transportation Statistics Office, Florida Department of Transportation, 2015) brought in Dock et al. (2017). A robust set of mobility and system coverage measures are mentioned in the sourcebook that cover all modes (i.e., all surface modes, aviation, and seaports). System performance is divided into four broad categories: quantity, quality, accessibility, and utilization.

One study claims that transportation accessibility "is the measure that truly represents the success of multimodal transportation systems from both the eyes of users and transportation practitioners" (Tasic & Bozic, 2017). The paper further presents spatio-temporal accessibility measures for pedestrians, bicyclists, and transit users using the City of Chicago as a case study.

Sanders et al. (2010), similar to other named studies, recommends first identifying broad objectives and goals for the project, and then adopting performance measures to suit those goals. The study identifies five broad goals for a public agency (the study is particularly making suggestions to CalTrans but they note that these can be adopted by other agencies as

well) including safety, mobility, delivery, stewardship, and service. They also identify "complete and green street measures" which can measure progress towards the broad objective of multimodality. They also set forth a list of measures which we highlight only a number of them below.

For pedestrians and bicyclists, Sanders et al. (2010) proposed safety performance measures including: pedestrian fatality rate per walking trip; pedestrian injury rate per walking trip; bicyclist fatality rate per bicycling trip; and the number of pedestrian/bicyclist collision hotspots on urban arterials. In addition, they suggest some key system mobility measures, including: the ratio of sidewalk mileage to centerline roadway mileage, bidirectionally on urban arterials; the ratio of Class II bicycle facility mileage to centerline roadway mileage, bidirectionally on urban arterials; percentage of intersections that are ADA compliant; number of pedestrian trips on urban arterials; and number of bicycle trips on urban arterials.

Figure 4 compares the recommended processes for project evaluation and performance measure development, highlighting key themes mentioned by three of the most relevant and thorough studies (Elefteriadou et al., 2012; Lasley, 2016; Seskin et al., 2015). Table 1 compares the recommended goals and objectives, along with dimensions for characterizing performance measures, as found in a selection of the most relevant published papers.

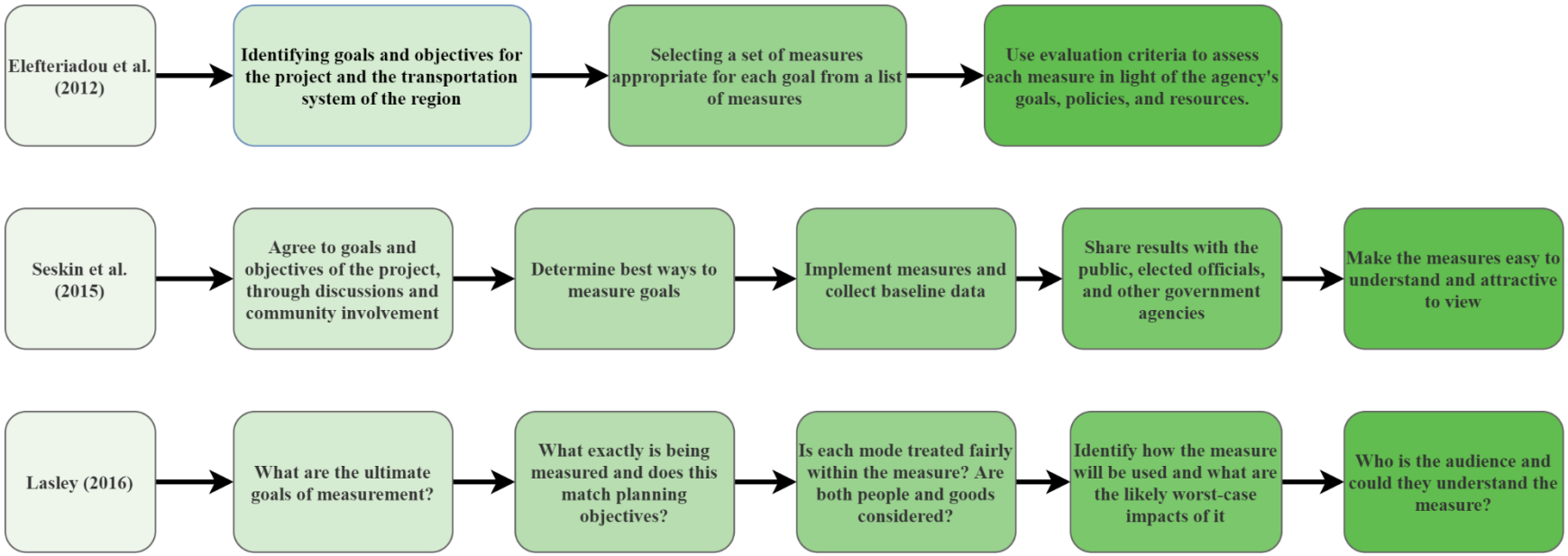

Figure 4: Processes for developing performance-based measures and evaluating projects

Table 1: Characterizing the literature by recommended goals for projects, dimension provided for the performance measures, and list of performance measures provided

Study	Recommended Goals and Objectives	Dimensions for Characterizing the Measures
Elefteriadou et al. (2012)	(1) Minimize ecological impact, (2) Increase accessibility, (3) Increase non-SOV travel, (4) Reduce congestion, (5) Optimize freight movement, (6) Enhance safety, and (7) Reduce air pollution	1- Infrastructure and environment (Density, Diversity, Design, Destination, and Accessibility); 2- Demand and system utilization (Auto, Transit, Freight, Non-motorized, Multimodal, and Travel Demand); 3- User Perceptions (Time-Related, Quantity-related, Reliability, Occupancy, Service Availability, Operation, Trip generation, and Mode Share); 4- Safety (History and Risk management); and 5- Sustainability (Ecological, Fiscal, and Social)
Seskin et al. (2015)	(1) Access; (2) Economy; (3) Environment, (4) Place, (5) Safety, (6) Equity, and (7) Public Health	-
Lasley (2016)	-	1- Quantity (volume or tonnage); 2- Effectiveness (person or vehicle throughput per hour); 3- Efficiency (travel time or delay); 4- Competitiveness (reliability or cost); 5- Connectivity (LOS measures or connectivity to other modes and/or facilities); and 6- Safety
Sanders et al. (2010).	(1) Safety, (2) Mobility, (3) Delivery, (4) Stewardship, and (5) Service	-
Dock et al. (2017)	-	1- Congestion; 2- Reliability; and 3- Accessibility

2.2.8 Supply- vs. Demand-based performance measures

A recurring theme in the literature is the difference between supply- and demand-based performance measures. Demand-based measures focus on how much a facility is serving users (e.g., the number of bicycle trips on the urban arterial per day). In contrast, supply-based measures emphasize the opportunities provided by facilities (e.g., ratio of bicycle facility mileage to roadway mileage). Metrics such as Multimodal LOS are also performance measures themselves although they tend to focus more on the supply-side of the facility and "what it has to offer" rather than "how much it is being used".

Lee & Miller (2017) emphasize the importance of differentiating between supply-based measures and demand-based measures. Their study included a literature review on this topic. They also argue that some methodologies want to measure what level of multimodality their facility design is supplying to the user while others measure the level of usage of their facility by different modes. For example, the "complete street score" is a supply-based measure that evaluates how a facility serves pedestrian, transit, auto, and bicycle users, based on criteria established by the community (e.g., a street passing through town should serve both transit riders and bicyclists) (Kingsbury et al., 2011). A second example for a supply-based measure is MMLOS provided in Dowling et al. (2008), which is more operational-focused and evaluates auto driver, bus passenger, bicyclists, and pedestrians. Criteria such as pavement conditions or lateral distance of bicyclist from drivers are considered in this methodology, among other mainly supply-based characteristics of the corridor. On the other hand, an example of a demand-based measure is indirectly implied by (Grant et al., 2012), where the use of a facility by non-auto modes implies a greater level of multimodality.

Lee & Miller (2017) then imply that there is a lack of a suitable framework that can assess multimodality through looking at supply and demand simultaneously. They use probability

theory and principal component analysis to create a new indicator based on both supply and demand (i.e., modal shares and monetary investment for each mode).

Another study also notes the difference between supply- and demand-side methodologies and implies that quality-of-service methodologies are considered "supply-side" assessments since they are an evaluation of existing facilities (Phillips et al., 2001). A problem with supply-side assessments is that they do not predict or estimate future demand. They are, however, very valuable for decision-making purposes regarding investments. On the other hand, demand-side methods are used to generate quantitative estimates of demand for multi-modal facilities, such as methods that assess potential demand levels rather than actual demand. The study further encourages the use of supply-side methodologies in coordination with some of the demand-side assessments, especially when demand is associated with the quality of existing facilities (Phillips et al., 2001).

Another topic includes looking at multimodal performance through the lens of achieving intermodal integration (Kanafani et al., 2010). For achieving intermodal integration, there needs to be a multimodal level of service measure or similar tool that shows the connections between involved modes of a system (Kanafani et al., 2010).

For demand-based measures, a common theme mentioned in several studies was the lack of data for measuring the true performance of a system in terms of facility usage. A study by Barbeau et al. (2020) finds a solution in applying big data for improving transportation measurement, particularly that of public transit through data sources such as GTFS and AVL. Another study (Sinclair et al., 2019) also indicates that the use of smartphone data from companies such as Google and Apple could help make up for the lack of facility-based data when measuring multimodal network performance by using individual trip-based data from

smartphones rather than from facilities. However, there are privacy concerns when it comes to disclosing those data, in addition to it not aligning with the companies' business models.

2.2.9 Conclusions

This literature review examined the history of multimodal approaches in transportation design and methods for multimodal performance-based design. We found that in reaction to decades of auto-centric design, there is an ongoing shift towards multimodal design. There are a number of multimodal level of service methods and multimodal performance measures available in the literature, however, none of them may serve as an “ideal” performance measure since the needs of projects are inherently different from each other.

The approach suggested by several studies is that an agency should identify and define its own performance measures for each project through evaluating their broad and project-specific goals and the available data that they have. A summary of suggestions regarding performance-based design are set forth below:

- The goals and objectives of the project should be identified as a first step. These goals could be generic and broad terms such as safety, reliability, utilization, etc. or could also be more specific such as "reducing pedestrian fatality rate to amount X by year Z".

- Performance measures can be adopted through a readily available list for the analysts to choose from. Two extensive lists of performance measures are available in the literature, throughout Seskin et al. (2015) and in Appendices A & C of Elefteriadou et al. (2012).

- Once performance measures are selected, the analysts should identify required data sources to reach those goals.

- One mode should not be sacrificed against the other.

- Performance measures used for a project should be a combination of supply-based and demand-based measures, not just focusing on one side in favor of the other

2.3 Review of best practices

The second task of the project involved getting an understanding of the state of the practice in multimodal and performance-based design. We first review certain definitions and terminology from the viewpoint of more practical documents. We then highlight the results of our interviews with several officials from DOTs and industry experts to see which states are multimodal leaders and what documents are especially relevant. Then, we report on some of those documents and synthesize the best practices outlined in them for finding performance measures, conducting trade-off examinations, data required for performance measures, low-cost data acquisitions methods, and general design processes.

2.3.1 Key terminology and antecedents to multimodal design

2.3.1.1 Practical design

The concept of practical design started in 2005, when the Missouri DOT stated their new strategic objective, to “build good projects everywhere – rather than perfect projects somewhere” (Neuman et al., 2016). Financial pressure led to the innovative approaches in project delivery and funding (Neuman et al., 2016). The term practical design is defined as "an approach to road and street engineering that prioritizes economy and seeks to optimize return on capital investment across the entire highway program and system. Its goal is a use of public funds that results in the best possible highway system" (MnDOT, 2018). This is not necessarily a new or unique concept as there has always been careful attention to economy and investment in engineering. The practical design movement is a "rediscovering of and refocusing on these principles", and is becoming more important due to downward trends in revenue and investment (MnDOT, 2018). Some natural outcomes of this movement are that it encourages design flexibility and considering a variety of design values, using evidence-

based techniques that will yield high returns on investment, and financial sustainability within the long-term fiscal outlook (MnDOT, 2018).

2.3.1.2 Performance-based design

Another increasingly popular term in recent years is performance-based design. Performance measures were defined in the previous literature review section; nevertheless, it is important to revisit these definitions from the standpoint of practical documents. Minnesota Department of Transportation (2018) defines performance-based design as "a design that involves determining design features in order to achieve desired outcomes and solve identified problems, based on known direct effects of physical roadway features on actual performance." Cambridge Systematics, Inc. (1999) also defines performance measurement as "the use of statistical evidence to determine progress toward specific defined organizational objectives". NCHRP Reports 785 (Performance-Based Analysis of Geometric Design of Highways and Streets) and 839 (A Performance-Based Highway Geometric Design Process) are also important practical documents that guide practitioners about performance-based design processes.

Combining the two aforementioned concepts results in Performance-Based Practical Design (PBPD). This approach is the use of performance-based processes and methods to solve problems while realizing there are limited monetary resources and that public funds must be spent wisely with a long-term, system-wide outlook (MnDOT, 2018).

NCHRP Report 785 sets forth a fundamental model for understanding the desired outcomes of a project, establishing and selecting performance measures that align with those outcomes, evaluating the performance of various alternative geometric design decisions, and reaching solutions that achieve the desired outcome while ensuring they are financially feasible (Ray et al., 2014). This process is shown in Figure 5. NCHRP Report 839 points out that

throughout history, design decisions have largely been based on specified design values and dimensions, and that highway and street design processes rely on standards that set minimum design feature values or ranges of values (Neuman et al., 2016). These dimensions that came from physical or mathematical models at the time, were intended to provided operational safety, efficiency, and comfort for the road user and were once thought to automatically provide good performance, while it is difficult or impossible for a designer to quantitatively display how the facility will perform based on these dimensions (Neuman et al., 2016). For example, minimum values or ranges for a facility's lane width that come from a table based on other dimensions such as design speed, do not guarantee good performance and do not by themselves quantitatively characterize how the project will perform and satisfy goals such as throughput, travel time, etc. In other words, engineers need performance metrics to measure their progress towards their project goals and objectives

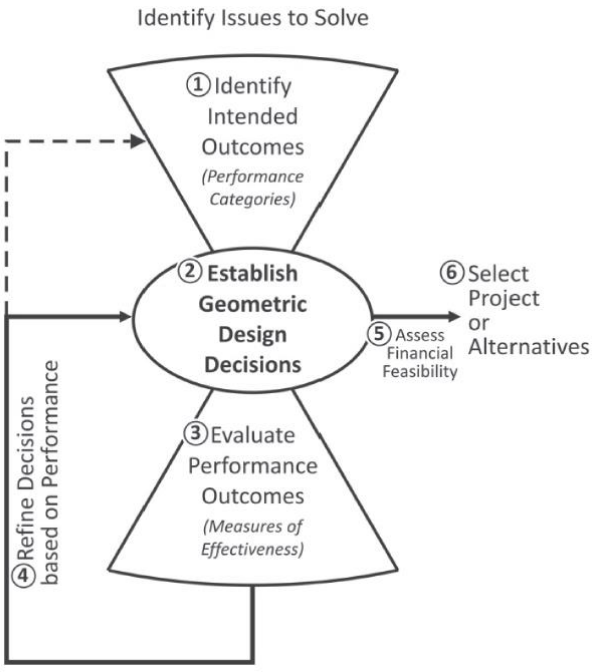

Figure 5: The fundamental model for performance-based analysis of geometric design of highways and streets (Ray et al., 2014)

A standard dimension that might have once been suggested as a performance goal, can no longer necessarily be considered as a desired outcome (Ray et al., 2014). Performance-based

practical design focuses on actual functional performance. Documents such as MnDOT's PBPD guidelines define broad performance characteristics such as: quality of service, safety, reliability, accessibility, infrastructure integrity, ease of use, ease of maintenance, visual quality, fit to context and community (MnDOT, 2018).

2.3.2 Informational interviews for identifying leaders in multimodal design

We identified multimodal planning and design experts from a list of participants in the Transportation Research Board 2021 Annual Conference's multimodal subcommittee virtual meeting. We sent 13 emails to a combination of USDOT (FHWA), state DOT, local DOT, and industry experts, asking for 15 minutes of time to talk about agencies and jurisdictions that are considered multimodal leaders and recommendations of state or local design manuals that are especially relevant to our research. We received nine responses that consisted of five state DOT officials and four industry experts, whose names and employers are kept anonymous.

The interviewees helped identify local or state jurisdictions that had done previous work regarding multimodal design, performance-based design, context-sensitive solutions, and complete streets, and/or had some level of documentation for these topics in their design manuals, handbooks, or guidebooks. All but one state DOT interviewees, in addition to identifying other state or local multimodal leaders, identified their own agency as having done some level of work in these fields. On average, each DOT representative identified about seven jurisdictions as multimodal leaders (including themselves), whereas each industry expert identified about 8 leaders on average (particularly, one of the experts highlighted 19 jurisdictions leading to a higher average).

Our interview protocol began with a brief two-minute introduction of the research project and then moved to five open-ended questions, although not every interview included all five

questions. The discussion for some questions was more detailed and automatically led to the responses we were looking for to our other questions. We specified that by multimodal, we meant active transportation (e.g., pedestrians, bicycles), freight (e.g., trucks, delivery vans, etc.), transit (e.g., buses, trains, paratransit), and single-occupant vehicles, and asked them to incorporate information about all these modes in their response. The questions then asked were as follows:

- Are there any ongoing activities for expanding and pushing multimodal transportation forward in your own state? If so, could you elaborate on those efforts?
- Where could we learn more about these efforts in your state (i.e., online resources, particular design manual chapters, etc.)?
- Are there other design manuals or documents belonging to other states that could be identified as especially relevant to our research?
- In particular to performance measures, and data needs for different modes in multimodal transportation, what resources can be identified?
- Do you have examples in your community where this new multimodal approach was implemented? Has it made a difference and was it a helpful difference or not?

Table 2 shows the results of our interviews. The table shows the four jurisdictions that were ultimately chosen as multimodal practice leaders to compare to WSDOT, with their votes highlighted. Massachusetts had the highest number of votes with seven, Minnesota was next with six, Florida had five, and Michigan had four. However, we elected not to examine Michigan because Minnesota is in the same region and had more votes. Instead, we selected as the last state Oregon, which had three votes. There were also three other jurisdictions with

three votes, i.e., Wisconsin DOT, Washington DOT, and Portland, OR. Wisconsin was also not chosen because there was already Minnesota, chosen from the Midwest. Washington was not chosen as this project was conducted for WSDOT and we aimed to identify other jurisdictions. Portland, OR, however, was a viable choice but Oregon DOT was determined a better fit given its status as neighboring state transportation department.

Interview highlights include:

- At least two of interviewees pointed out to Massachusetts DOT's (MassDOT) Bike Facilities Guide and that it stood out among other practical guidelines. One interviewee noted that Massachusetts adopted context-based design earlier than other jurisdictions, continues to improve their Project Development and Design Guide, and excels at the context-sensitive and multimodal aspects of design.

- Florida DOT (FDOT) was acknowledged as a leader for their efforts to transition to context-based design and context-sensitive guidelines. FDOT has a thorough context classification document and has held several workshops in recent years including workshops for complete streets and context-based design.

- Minnesota was praised for its bike facility guidelines, its performance-based practical design guidelines, as well as its documentation efforts, and Oregon DOT was especially praised for their Blueprint for Urban Design (BUD).

- Interviewees identified two NCHRP reports as especially relevant. NCHRP Report 785 (Ray et al., 2014) provides a principles-focused approach that looks at the outcomes of design decisions as the primary measure of design

effectiveness. The report presents methods to incorporate performance-based analysis into the project development process. NCHRP Report 839 recommends a new highway geometric design process that is more aligned with the current expectations of transportation agencies and communities by focusing on transportation performance rather than the selection of values from tables of dimensions.

- One interviewee noted that a particular county they know of is moving entirely away from functional classification of roadways towards context classification exclusively.

- Finally, one expert noted the decline in the incidence of performance measures in design manuals and greater emphasis on design processes and tailoring measures to projects.

Table 2: Results of informational interviews for identifying multimodal leaders based on U.S. region and state/local jurisdiction

Region	Type	Jurisdiction Name	State DOT (A-E)					Industry Expert (F-I)				Total
			A	B	C	D	E	F	G	H	I	
West	State	California DOT	✓						✓			2
		Oregon DOT		✓						✓	✓	3
		Washington DOT	✓	✓						✓		3
	Local	Denver, CO	✓							✓		2
		Portland, OR	✓	✓						✓		3
		Seattle, WA								✓		1
Southwest	State	Arizona DOT			✓							1
	Local	Austin,TX								✓		1
		Dallas County, TX								✓		1
		Maricopa County, AZ								✓		1
Midwest	State	Illinois DOT					✓	✓				2
		Michigan DOT	✓			✓	✓			✓		4
		Minnesota DOT		✓	✓		✓	✓	✓	✓		6
		Ohio DOT								✓		1
		Wisconsin DOT					✓	✓	✓			3
	Local	Ann Arbor, MI	✓				✓					2
		Columbus, OH								✓		1
		Chicago, IL	✓					✓				2
		Grand Rapids, MI					✓					1
Southeast	State	Florida DOT	✓		✓	✓	✓		✓			5
		Georgia DOT						✓				1
		North Carolina DOT				✓	✓			✓		3
		Tennessee DOT								✓		1
		Virginia DOT	✓		✓							2
	Local	Charlotte, NC								✓		1
		Raleigh, NC								✓		1
		New Orleans, LA			✓							1
Northeast	State	District (DC) DOT	✓						✓			2
		Maryland DOT							✓	✓		2
		Massachusetts DOT	✓	✓	✓	✓	✓			✓	✓	7
		New Jersey DOT				✓						1
		Pennsylvania DOT								✓		1
	Local	Cambridge, MA	✓									1
		New York City, NY	✓						✓			2
		Somerville, MA	✓									1
		Total	14	5	6	5	9	5	7	19	2	

2.3.3 A review of jurisdictions' available documents in multimodal, performance-based, and/or practical design

Table 3 shows the key documents referenced in our interviews for each of the final four states. We next summarize what distinguishes these documents as "best practice".

Table 3: List of documents for the selected four jurisdictions

Document type	FDOT	MnDOT	MassDOT	ODOT
Main Design Manual	- FDOT Design Manual (FDOT, 2020a) - Florida Greenbook (FDOT, 2016)	- Road Design Manual (MnDOT, n.d.)	- Project Development and Design Guide (MassHighway, 2006)	- Highway Design Manual (ODOT, 2012)
Other Design Guidelines	- Context Classification Guidelines (FDOT, 2020b) - Transit Facilities Guideline (FDOT, 2017) - Context Classification Framework for Bus Transit (Kittelson & Associates, Inc., 2020)	- Performance-Based Practical Design Process and Design Guidance (MnDOT, 2018) - Bicycle Facility Design Manual (MnDOT, 2020)	- Separated Bike Lane Planning & Design Guide (MassDOT, 2015) - Guidelines for the Planning and Design of Roundabouts (MassDOT, 2020)	- Blueprint for Urban Design (BUD) Volumes 1 & 2 (ODOT, 2020a, 2020b)
Transportation Plans	- Complete Streets Implementation Plan. M2D2: Multimodal Development and Delivery (FDOT & Smart Growth America, 2015)	- Statewide Bicycle, Pedestrian, Multimodal, and other Transportation Plans		- Oregon Transportation Plan

2.3.3.1 FDOT

The FDOT Design Manual (FDM) serves as the main design guide for the State of Florida. Chapter 1 of the design manual covers project development and Chapter 2 covers design criteria. The FDM replaced FDOT's Plans Preparation Manual (PPM) (circulated since 1998) in January 2018. The department has another important document titled FDOT Context Classification Guidelines (FDOT, 2020b) that classifies Florida's roads into eight different contexts. They also have policies, guidelines, and implementation plans for Complete Streets

projects. The FDM also has subchapters on pedestrian facilities (222), bike facilities (223), shared-use paths (224), and public transit facilities (225). Intersections are in chapter (212) and modern roundabouts in chapter (213).

Florida DOT leads in its use of context classification and context-sensitive solutions (CSS) as well as their complete streets program. Interviewees noted that Florida moved to context classification earlier than several other states and that their detailed CSS guidelines provide state-of-the-art guidance for their engineers and practitioners in designing facilities that serve all modes according to the land context. The Florida Greenbook (FDOT, 2016) provides uniform minimum standards and criteria for the design, construction, and maintenance of all public streets and highways, including pedestrian and bicycle facilities, in the State of Florida.

FDOT was also able to fit its bike and transit guidelines within the CSS framework according to one of our interviewees. Their public transit office has several documents that provide technical guidelines in transit facilities designed to facilitate transit operations on and off the roadway system. Their Context Classification Framework for Bus Transit (Kittelson & Associates, Inc., 2020) provides illustrations pointing out the basic and desired elements for transit facilities (i.e., bus lanes, bus stops, etc.) with respect to Florida's eight different contexts. Furthermore, their Transit Facilities Guidelines (FDOT, 2017) provides design drawings for various transit facilities. FDOT updates their design manual rapidly, bringing in newer guidance for all transportation modes, which is another reason they are identified as multimodal leaders.

2.3.3.2 MnDOT

MnDOT has a Road Design Manual (RDM) that is now being transitioned into its successor document, the Facility Design Guide (FDG). Both publications are now active on their website, and as new parts of the FDG are published, the corresponding RDM parts will be removed from the website, with linked FDG reference substituting their place. However, the FDG is not complete yet, and therefore, the RDM was used to characterize their design processes. They also have a Performance-Based Practical Design Process and Design Guidance (MnDOT, 2018) document that provides information on what performance-based design and practical design are and what they intend to do. This document addresses why these approaches are needed today and offers some details of how to implement this approach. However, it does not provide a full set of performance measures for project evaluation.

MnDOT also has a Bicycle Facility Design Manual (MnDOT, 2020) which complements the RDM with guidance on planning, designing, and maintaining bicycle facilities. The state also has dozens of two to three page “infosheets” on such topics such as a paved shoulders and side paths, each providing concise guidance on a particular matter. Interviewees complimented MnDOT’s effective documentation and practice of publishing this guidance on their website.

The department also has several statewide system plans, including a Statewide Bicycle System Plan, Pedestrian System Plan, Transit Plan, Freight Plan, ADA Transition Plan, and more importantly a Statewide Multimodal Transportation Plan. An overview of the DOT's plans is shown in Figure 6. All these plans provide some level of insight into the future and establish the visions and goals that the state has for the years ahead. In particular, the Statewide Multimodal Transportation Plan (MnDOT, 2017) is a 20-year plan based on the

Minnesota GO vision and is the highest level policy plan for all transportation modes that aims to maximize the health of the people, the environment, and the economy. The document outlines the Minnesota GO Vision, discusses the current state of the state's transportation system, and reviews key trends in the state's economy, population, environment, and transportation plan. The document also provides guidance on how they plan to move forward by presenting objectives, performance measures, and strategies to move towards their two-decade vision. The performance measures provided in the document are mostly broad, state-level measures such as system reliability and delay measures for the interstate and national highway system, average annual aircraft delay, annual transit on-time performance, percentage of state-owned sidewalk miles compliant with ADA standards, annual greenhouse gas emissions from the transportations sector, etc. All of these measures look at the transportation system as a whole, rather than serving as performance measures for one single project (MnDOT, 2017).

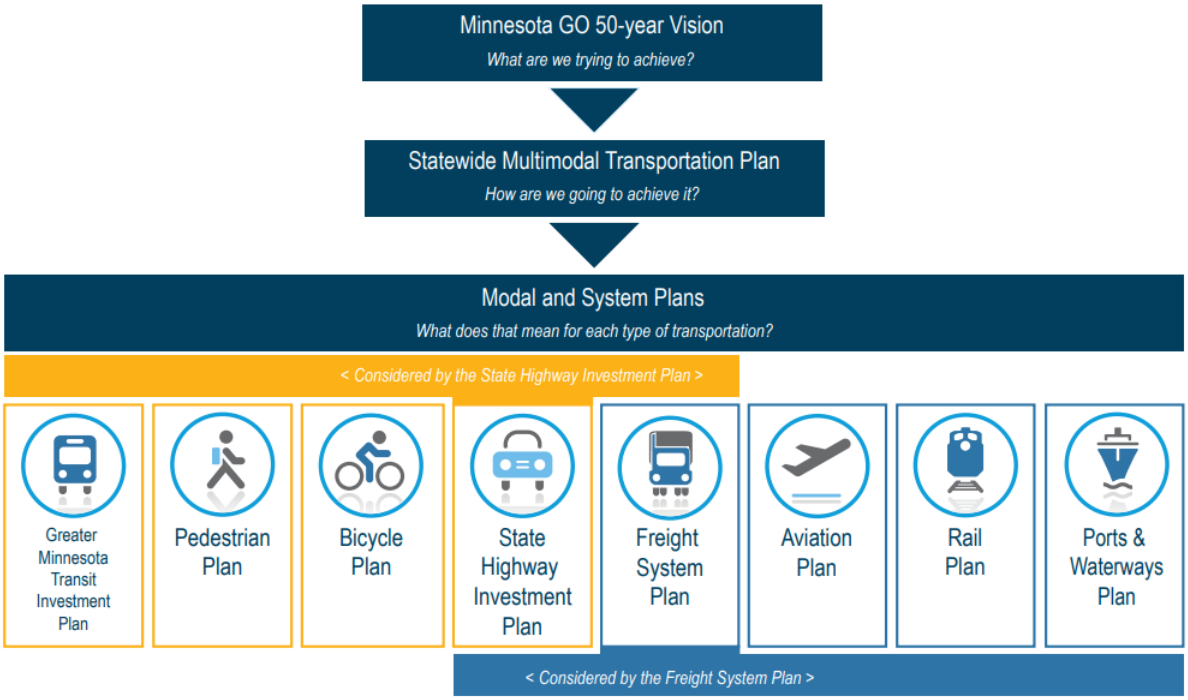

Figure 6: MnDOT family of transportation plans (MnDOT, 2017)

2.3.3.3 MassDOT

Massachusetts DOT was the jurisdiction with the most votes as a multimodal practice leader in our interviews. Several interviewees pointed to their innovative project development and design guidelines which take both multimodal and context-based design into consideration. MassHighway's Project Development and Design Guide (MassHighway, 2006) sets several goals for the project development process from concept to construction, including: (1) to ensure context sensitivity through open dialog between project proponents, reviewers, the public, and other parties; (2) to think beyond the pavement to achieve the optimum accommodation for all modes; (3) to encourage early planning, public outreach, and evaluation to identify project needs, objectives, issues, and impacts before expanding significant resources; (4) to "achieve consistent expectations and understanding between project proponents and those entities who evaluate, prioritize, and fund projects"; and (5) to ensure resources are allocated to projects that address local, regional, and statewide priorities and needs.

MassDOT's Separated Bike Lane Planning & Design Guide (MassDOT, 2015) was also mentioned by several interviewees who noted the guide was ahead of its time when released in 2015. This document supplements the bicycle facility design advice in the Project Development & Design Guide (Chapters 5 and 6) by providing guidance on where to implement separated bike lanes as well as how to design them as part of a safe and comfortable network of bicycle facilities. In addition, MassDOT's Guidelines for the Planning and Design of Roundabouts was referred to several times by our interviewees.

MassDOT's design manual, titled "Project Development and Design Guide", essentially divides a project into two parts: project development and design. Chapter 1 of the book has some general introductions, and Chapter 2 talks about the project development step, whereas

Chapters 3 to 14 are basic design chapters. Chapter 3 talks about basic design controls, while Chapter 4 establishes parameters for designing horizontal and vertical alignments of streets and highways. Chapter 11 has info on shared-use paths and greenways. Chapter 12 has info on intermodal facilities and rest areas including park & ride facilities and transit centers. Other chapters include intersection design, interchanges, bridges, access management, etc. They develop an eight-step project development process to move a project from problem identification to completion, which can be seen in Figure 7.

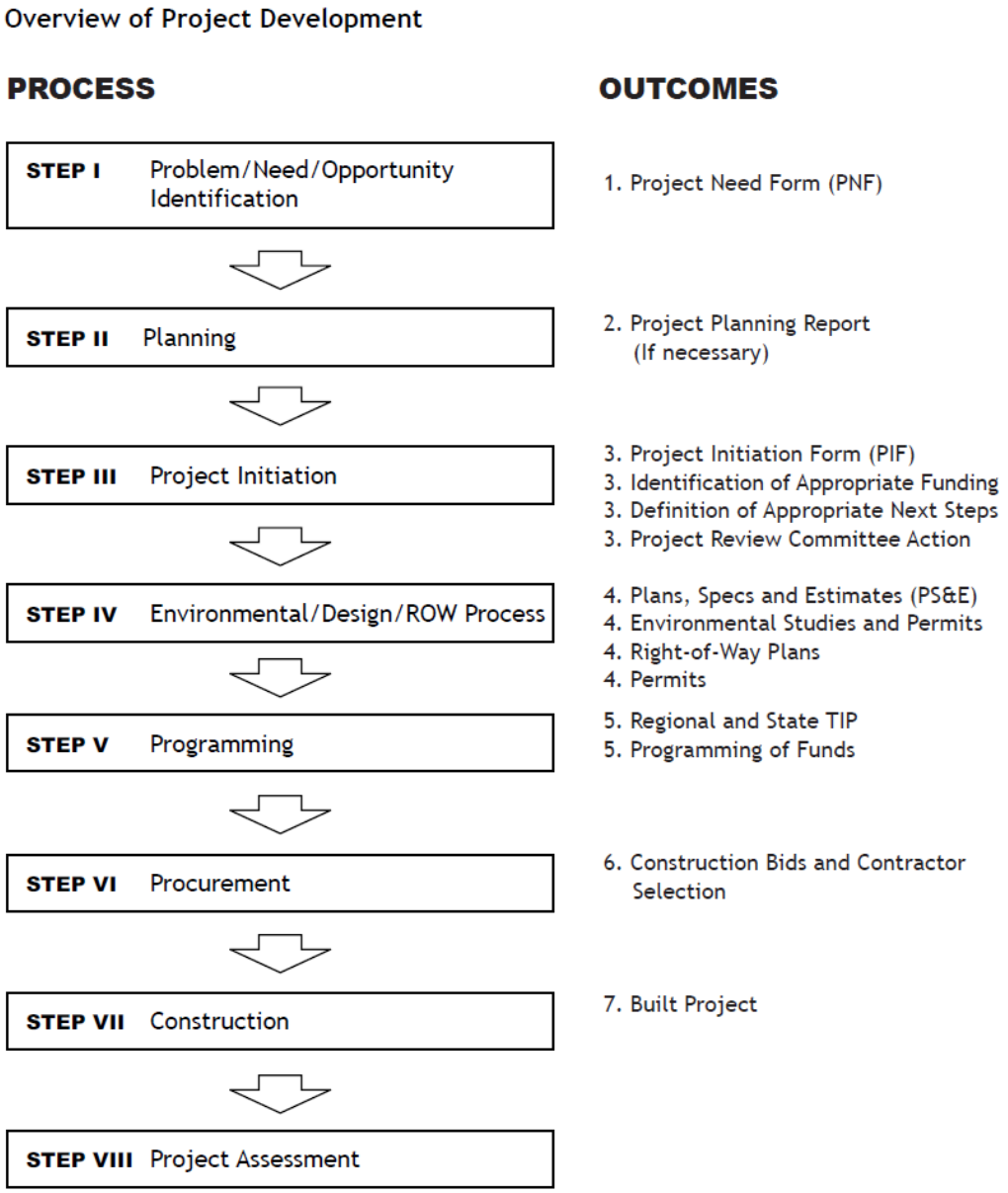

Figure 7: Overview of MassDOT's project development steps (MassHighway, 2006)

2.3.3.4 ODOT

ODOT uses two primary sources for their design: 1) the ODOT Highway Design Manual; and 2) the Blueprint for Urban Design (Volumes 1 & 2). These two documents complement each other and are used by all ODOT engineers for designing facilities. Our interviewees appreciated the Blueprint for Urban Design for having innovative guidance on urban contexts and roadway classification, design flexibility, and a multimodal decision-making framework. ODOT also uses its Project Delivery Guide (ODOT, 2017) to provide step-by-step guidance in the development and delivery of projects from transportation planning to constructing management transition. Figure 8 displays the ODOT Transportation System Lifecycle.

ODOT also relies on the Oregon Transportation Plan (OTP) to provide a system-wide context for project selection and design. There is an OTP amendment on performance measures that has guidance on performance-based statewide transportation planning processes. In addition, Oregon Highway Plan includes federal requirements for tracking certain performance measures.

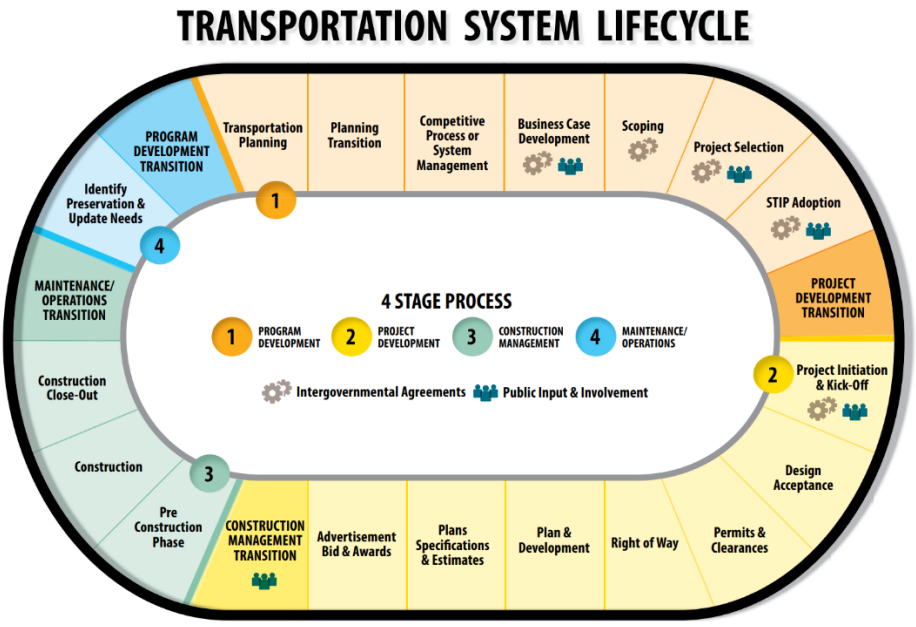

Figure 8: ODOT's transportation system lifecycle (ODOT, 2017)

2.3.3.5 NCRHP Report 839

NCRHP Report 839: A Performance-Based Highway Geometric Design Process provides a geometric design process for highways that focuses on the transportation performance of facilities rather than design dimensions. The report starts by reviewing a history of highway design from the 1940s up until the 2010s and shifts in project needs and design processes for 10-year periods. The report describes a movement towards more flexibility in design to help transportation projects meet the needs of multiple stakeholders, and due to these shifts, the emergence of alternative design concepts that have become part of the practice (Neuman et al., 2016). These emerging concepts include the: (1) complete streets concept; (2) concept of Context Sensitive Design - CSD (now often referred to as Context Sensitive Solutions - CSS); (3) concept of performance-based design; (4) concept of practical design; (5) the design matrix approach; (6) the safe systems approach; (7) concept of travel time reliability; (8) concept of Value Engineering (VE); (9) concept of designing for 3R (Reconstruction, Rehabilitation, Resurfacing) projects; and (10) concept of design for Very Low-Volume Local Roads (VLVLR) (roads with ADT $\leq$ 400) (Neuman et al., 2016). Each of these alternative design concepts and how they achieve their goals are briefly described in the report. Table 4, taken from Neuman et al. (2016), lists important insights from these design processes and illustrates how they compare and overlap across these various initiatives. One key takeaway from this table is that from the 10 alternative design processes, only two highlight that roads serve all road users and not just motor vehicles (multimodal design), namely, complete streets and CSS. The report describes a new geometric design approach informed by these various concepts that focuses on transportation performance.

Table 4: Alternative design processes and initiatives overlaps (Neuman et al., 2016)

Important Insights for the Geometric Design Process	Alternative Design Processes and Initiatives										
	Complete Streets	CSD	Performance-Based Design	Practical Design	Design Matrix	Safe Systems	Travel Time Reliability	Value Engineering	Designing for 3R	Designing for VLVLR	Systemic Safety
Roads serve more than just motor vehicles	●	●									
Road design involves many different disciplines	●	●	●			●		●	○		
Context matters and it varies	●	●	○	○	●	○	○	○		●	●
Performance (operational, safety) is important		○	●	●	●	●	●	○			●
Performance may have many dimensions	●	●	●	●	●		●	○	○		
Safety performance should focus on elimination or mitigation of severe crashes			○	○	○	●		○		○	●
Speed and crash severity are closely linked			●			●					
Existing roads with known problems are different from new roads				●	●				●	○	●
Traditional design approaches are believed by professionals to yield suboptimal results	●	●		●	●			○			○
Focusing on identifying and addressing the problem(s) should be central to developing design solutions	○	○	●	●	●		○	●	○		●
Safety risk and cost effectiveness are related to traffic volume			●		●				○	●	●

Note: ● Fully applies ○ Partially applies

2.3.4 Comparison of project development and design processes through key design steps and elements

In this section we compare the design processes for the four peer states, WSDOT's process, and the design process identified in NCHRP Report 839 together. Table 5 gives a summary of the project development and design processes with the left-most column showing the 11-step process from NCHRP 839 and the remaining columns showing how the states map to this framework. The table shows that the design processes for all jurisdictions share some common traits while some have more details than others. Table 6 shows a summarized version of which jurisdictions follow which steps, including two more steps for a total of 13.

Table 7 shows a comparison of the various context classifications that these states describe. Lastly, Table 8 compares the design controls of the various jurisdictions.

All the jurisdictions start their design by identifying a need or problem. They work to clearly develop a need statement in the first step without prescribing a solution at the start. In the next step, the design lead identifies and charters a group of project stakeholders including those internal and external to the agency. This step also involves public outreach for some of the jurisdictions.

The project team refines and confirms the problem or need statement to then inform the development of alternatives and the selection of the preferred project scope. The scope will establish the project type such as a new road, reconstruction, or 3R (reconstruction, rehabilitation, and resurfacing). Next, the team evaluates the project context and geometric design criteria using a context-based classification or context-sensitive. The team identifies design controls such as target speed, traffic volumes, LOS, and road user attributes. Next, the team applies the appropriate geometric design process and criteria to the project.

Once the geometric design is complete, an inclusive and interdisciplinary team evaluates geometric alternatives that address the need or solve the problem, within the context conditions and constraints. The team then makes key design decisions and generates documentation to inform the final design decisions before transitioning to final engineering. In the aftermath of the project, continuous monitoring and feedback allow the responsible agencies to evaluate the project's performance relative to the design goals.

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Table 5: Summary of the design processes for WSDOT, FDOT, MnDOT, ODOT, and MassDOT, all compared to NCHRP 839's design processes guidelines

No.	NCHRP 839	WSDOT	FDOT	MnDOT	ODOT	Mass DOT
1	Define the Transportation Problem or Need	• Clearly identify the baseline need. Define it in terms of performance, contributing factors, and underlying reasons for the baseline need (Chapter 1101 of design manual). • Identify the objective, in simple, direct terms. • Identify the performance metric(s) involved. • Include one or more quantifiable statements. • Exclude any description or discussion of potential solutions.	Fully define and document the objectives of the project and the scope of activities to accomplish them (FDM 110.2)	The earliest step in the design process is determining project purpose, need and problems followed by establishing desired outcomes and goals. (MnDOT PBPD) Some key principles that MnDOT highlights for successful project development are: • Balance safety, mobility, community, and environmental goals in all projects. • Involve the public and affected agencies • Address all modes of travel • Apply flexibility inherent in design standards (MnDOT RDM p. 2-1(1))	Identify the problem and need for the project	Step I: Problem/Need/Opportunity Identification The proponent completes a Project Need Form (PNF). This form is then reviewed by the MassHighway District office which provides guidance to the proponent on the subsequent steps of the process" (MassHighway PDDG Exhibit 2-11)
2	Identify and Charter All Project Stakeholders • Internal Agency Stakeholders • External Agency Stakeholders • Other External Stakeholder Groups or Agencies • Directly Affected Stakeholders • Stakeholder Chartering	Engage local partners and stakeholders at the earliest stages of scope definition to account for their input at the right stage of the development process. Engage with the community to fully understand: • Performance gaps • Context identity • Local environmental issues • Modal priorities and needs (Chapter 1100)	Public Information and Outreach (FDM 104.2) and Community Awareness Plan (FDM 104.3): • Identify partners • Identify project stakeholders • Identify target audiences • Develop the message(s) • Determine communication strategies (more in the Florida Public Involvement Handbook) • Determine communication timing	Understand the classification of various highways according to who has responsibility for its maintenance, improvement, and traffic regulation (MnDOT RDM p. 2-2(1)): • Jurisdictional systems: Trunk highway system, County Highway system, township road system, Municipal city street system • State aid systems: County State Aid Highways (CSAH) and Municipal State Aid Streets (MSAS).		

No.	NCHRP 839	WSDOT	FDOT	MnDOT	ODOT	Mass DOT
3	Develop the Project Scope: Refinement and Confirmation of Problem or Needs Statement	Translate the need into specific performance metrics and select targets in accordance to what the design shall achieve. A contributing factors analysis (in Chapter 1101) refines focus in order to resolve the specific performance problems and helps define the potential scope of project alternatives.	The Department's project manager is responsible for the development, review and approval of the project objectives, scope of work, and schedule in accordance with the Project Management Guide. They must also verify that required funds are in the work program. (FDM)	• Project scoping: Identify system deficiencies and needs through operation monitoring, data from management systems (bridge, pavement, safety, etc.), maintenance problems, and public comments. (MnDOT RDM p. 2-4 (1)). • Consider (1) Project programming; (2) Cost-effectiveness policy; and (3) Value engineering		Step II: Planning "Project planning can range from agreement that the problem should be addressed through a clear solution to a detailed analysis of alternatives and their impacts." (MassHighway PDDG Exhibit 2-11) Step III: Project Initiation "The proponent prepares and submits a Project Initiation Form (PIF) and a Transportation Evaluation Criteria (TEC) form in this step. The PIF and TEC are informally reviewed by the Metropolitan Planning Organization (MPO) and MassHighway District office, and formally reviewed by the PRC." (MassHighway PDDG Exhibit 2-11)
4	Determine the Project Type and Design Development Parameters. Project types are: • New Roads • Reconstruction Projects • 3R (Reconstruction, Rehabilitation, and Resurfacing) Projects		Three basic types of projects: • New Construction • Add Lanes and Reconstruction • Other Projects (RRR, operational improvements, safety enhancements, etc.)	• The objectives and available funding for the project must be balanced early in the scoping process. There are three investment categories: (1) New construction / reconstruction, (2) Preservations, and (3) Preventive maintenance (MnDOT RDM p. 2-5 (2))	Types of Projects: • Modernization [New Construction/Reconstruction (4R)] • Preservation [Interstate Maintenance/Resurfacing, Restoration, and Rehabilitation (3R)] • Bridge • Safety • Operations • Maintenance • Miscellaneous/Special Programs • Single Function • ODOT Resurfacing 1R (ODOT HDM 1-15)	

No.	NCHRP 839	WSDOT	FDOT	MnDOT	ODOT	Mass DOT
5	Establish the Project's Context and Geometric Design Framework • Develop Project Evaluation Criteria Within the Context Framework • Establish Decision-making Roles and Responsibilities • Determine Basic Geometric Design Controls: • Design or Target Speed • Design Traffic Volumes • Design LOS • Road User Attributes	Identify the land use and transportation context (which includes environmental use and constraints) for the location (Chapter 1102). • Land Use Categories: (1) Rural, (2) Suburban, (3) Urban, and (4) Urban Core • Transportation Context: (1) Roadway type, (2) Bicycle route type, (3) Pedestrian route type, (4) Freight route type, (5) Transit use considerations, (6) Complete streets and Main Street highways	Establish and document the project's surrounding context: (FDM) • Functional Class: (1) Limited Access Facilities, (2) Principal Arterial, (3) Minor Arterial, (4) Collector, (5) Local Roads • Context Class: C1: Natural, C2: Rural, C2T: Rural Town, C3R: Suburban Residential, C3C: Suburban Commercial, C4: Urban General, C5: Urban Center, C6: Urban Core	• Functional classification: (1) Arterials, (2) Collectors, and (3) Local roads and streets (MnDOT RDM p. 2-5(1)) • Types of highways: (1) Two-lane, (2) multi-lane highways, and (3) scenic byways (MnDOT RDM p. 2-5(3))	Roadway Classification: (1) Statewide Highways, (2) Regional Highways, (3) District Highways, (4) Local Interest Roads (ODOT BUD) Context classifications: (1) Traditional Downtown/ Central Business District (CBD), (2) Urban Mix, (3) Commercial Corridor, (4) Residential Corridor, (5) Suburban Fringe, (6) Rural Community (ODOT BUD)	• Roadway Context (MassHighway PDDG Section 3.2): Area types: Rural, Suburban, Urban & Roadway types: Freeways, major arterials, minor arterials, major collectors, minor collectors, local roads and streets

No.	NCHRP 839	WSDOT	FDOT	MnDOT	ODOT	Mass DOT
Mass6	Apply the Appropriate Geometric Design Process and Criteria	• Select design controls compatible with the context (Chapter 1103). • Design controls create significant boundaries and have significant influence on design. WSDOT uses five primary design controls: (1) **Design Year**, (2) **Modal Priority**, (3) **Access Control**, (4) **Design Speed**, and (5) **Terrain Classification**	• The design controls addressed in this manual include: • **Context Classification**: Determines key design criteria elements for arterials and collectors. • **Functional classification** • **Level of service** • **Traffic and Design Year**: Satisfy capacity needs at an acceptable level of service through the design year. • **Access Management**: Regulation of access is necessary to preserve the functional integrity of the State Highway System and to promote the safe and efficient movement of people and goods within the state. • **Design Speed**: (1) High: 50 mph and greater, (2) Low: 45 mph and less, and (3) Very Low: 35 mph and less. • **Design Vehicle**: The largest vehicle that is accommodated without encroachment on to curbs (when present) or into adjacent travel lanes. (FDM)	Fundamental Design Controls (from PBPD) • **Level of Service**: PLOS, BLOS, and TPLOS. • **Design Speed** • **Design Vehicle** Other design parameters: • **Functional classification** (MnDOT RDM p. 2-5(1)) • **Types of highways** (MnDOT RDM p. 2-5(3)) • **Traffic characteristics**: (1) Volume, (2) Direction, (3) Distribution, (4) Composition, and (5) Traffic flow. (MnDOT RDM p. 2-5(5)) • **Speed** (MnDOT RDM p. 2-5(7)) • **Capacity** (MnDOT RDM p. 2-5(8)) • **Sight Distance**: Stopping sight distance, Passing sight distance, Decision sight distance should be considered. (MnDOT RDM p. 2-5(11)) • **Terrain**: (1) level, (2) rolling, and (3) mountainous. (MnDOT RDM p. 2-5(15)) • **Crash data**: Review crash history within project limits (MnDOT RDM p. 2-5(16))	Design control and criteria: • **Design vehicles**: the number and type of trucks, functional classification of the highway, freight route designation, and the effect on other modes including pedestrians and bicycles, should all be considered. • **Design speed**: The selection of a design speed is dependent on traffic volume, geographic characteristics, functional classification, number of travel lanes, 85th percentile speed, roadway environment, adjacent land use, and type of project . • **Access management**: Good access management will reduce the overall number of crashes and increase the highway's capacity • **Traffic Characteristics**: Four major components affect traffic characteristics: (1) Vehicles, (2) Facility character and functional requirements, (3) Drivers/users, and (4) Traffic demand (ODOT BUD)	Basic design controls: • **Roadway Context** (MassHighway PDDG Section 3.2) • **Roadway Users** (Section 3.3): Pedestrian, bicyclists, and drive • **Transportation Demand** (Section 3.4): Design year, volume and composition of the demand, • **Measures of Effectiveness** (Section 3.5): facility condition, safety, mode choice, network connectivity, level of service • **Speed** (Section 3.6): selecting vehicle, pedestrian, and bicycle design speed • **Sight Distance** (Section 3.7): recognizing sight distance for motor vehicles, bicyclists, and pedestrians

No.	NCHRP 839	WSDOT	FDOT	MnDOT	ODOT	Mass DOT
7	Designing the Geometric Alternatives • Assemble an Inclusive and Interdisciplinary Team • Focus on and Address the Need or Solve the Problem(s) Within the Context Conditions and Constraints	• Formulate and evaluate potential alternatives that resolve the baseline need for the selected context and design controls (Chapter 1104). • Alternative Solution Formulation • Alternative Solution Evaluation	• Establish geometry, grades, and cross sections and evaluate alternatives	Use value engineering principles to design alternatives: • Use creative thinking to speculate on alternatives that can provide the required functions. • Evaluate the best and lowest life-cycle cost alternatives. • Develop acceptable alternatives into fully supported recommendations. • Present/formally report all recommendations to management for review, approval, and implementation. (MnDOT RDM p. 2-4(2))	Work with different project team members to refine the selected alternative design (ODOT HDM)	Document all considered alternatives
8	Design Decision Making and Documentation • Independent Quality and Risk Management Processes	Select design elements that will be included in the alternatives (Chapter 1105).	✓	Document design decisions	Document design decisions	Document design decisions
9	Transition to Preliminary and Final Engineering	Determine design element dimensions consistent with performance needs, context, and design controls (Chapter 1106).	✓	✓	✓	✓
10	Agency Operations and Maintenance Database Assembly					
11	Continuous Monitoring and Feedback to Agency Processes and Database					

Table 6: Summary of design processes

Step	Tasks	NCHRP 839	WSDOT	FDOT	MnDOT	ODOT	Mass DOT
1	Define the transportation problem or need. Identify the objective, in simple, direct terms.	✓	✓	✓	✓	✓	✓
2	Include at least one quantifiable statement by identifying performance metric(s) involved		✓	✓			✓
3	Identify and charter all project stakeholders, including general public	✓	✓	✓	✓		
4	Prepare a community awareness plan, reaching out to the target audience			✓			
5	Develop the project scope: refinement and confirmation of problem or needs statement	✓	✓	✓	✓		✓
6	Determine the project type	✓		✓	✓	✓	
7	Identify the land use and transportation context for each mode	✓	✓	✓	✓	✓	✓
8	Select design controls compatible with the project context	✓	✓	✓	✓	✓	✓
9	Formulate and assemble other geometric alternatives that resolve the baseline need	✓	✓	✓	✓	✓	✓
10	Design decision making and documentation	✓	✓	✓	✓	✓	✓
11	Transition to preliminary and final engineering	✓	✓	✓	✓	✓	✓
12	Input core data into O&M databases for agency operations	✓					
13	Continuously monitor and fully utilize data coming in from the projects (e.g., ITS data)	✓					

Table 7: Context classification comparison across jurisdictions

No.	FDOT (Reference)	ODOT	WSDOT	MassDOT	MnDOT
1	C1: Natural	×	×	×	Even though they mention context-sensitive solutions and talk about rural vs. urban vs. suburban highways and streets several times, none of their documents explicitly mentioned context classification
2	C2: Rural	Rural Community	Rural	Rural	
3	C2T: Rural Town	Suburban Fringe			
4	C3R: Suburban Residential	Residential Corridor	Suburban	Suburban	
5	C3C: Suburban Commercial	Commercial Corridor			
6	C4: Urban General	Urban Mix	Urban	Urban	
7	C5: Urban Center	Traditional Downtown / Central Business District (CBD)			
8	C6: Urban Core		Urban Core		
No. of Classes	8	6	4	3	N/A

Table 8: Design control comparison across jurisdictions

Design Controls	WSDOT	FDOT	MnDOT	ODOT	MassDOT
Design speed	✓	✓	✓	✓	✓
Access classification, control, or management	✓	✓	✓	✓	
Design vehicle		✓	✓	✓	
Level of service		✓	✓		
Design period or year	✓	✓			
Functional classification		✓			✓
Context classification		✓			✓
Traffic volumes		✓			
Modal priority	✓				✓
Roadway users			✓ (drivers)		✓ (drivers, peds, and bikes)
Transportation demand					✓
Sight distance					✓
Measure of effectiveness (e.g., LOS, Safety, etc.)					✓
Terrain classification	✓				
Pedestrian and bicyclist traffic			✓		
Mass transit			✓		
Safety			✓		
Traffic characteristics (vehicles, modes, volumes)				✓	

After reviewing the design manuals and handbooks of the multimodal practice leaders, we also worked to identify documents that address performance measures and data sources recommended for project development. Two documents stood out. First is the ODOT Blueprint for Urban Design which includes a table that lists some performance measures that are useful for project evaluation across different modes, shown in Table 9.

Second, MassDOT's guidelines on Complete Streets also established a set of performance measures used for the development of Complete Street projects. These performance measures are listed by mode in Table 10.

Table 9: Example of ODOT's project-level performance measures by mode (ODOT, 2020b)

Mode	Performance Measures
Pedestrian	Pedestrian Level of Traffic Stress
	Multimodal Level of Service (simplified or full calculation)
	Sidewalk coverage and connectivity
	Sidewalk width
	Average distance between marked crossings
	Percent of ADA-compliant pedestrian crossings
	Average pedestrian delay at intersections
	Presence of pedestrian refuge Islands
	Degree of street trees and shade
	Level of pedestrian-scale street lighting
	Estimated potential reduction in crashes using crash reduction factors
Bicycle	Bicycle Level of Traffic Stress
	Multimodal Level of Service (simplified or full calculation)
	Percent of roadway served by an exclusive bicycle facility
	Percent of roadway with bicycle facilities meeting current standards
	Estimated potential reduction in crashes using crash reduction factors
	Forecast volumes of bicyclist (various methods available)
Transit	Number/percent of ADA-compliant transit stops
	Number of residents/jobs within a quarter mile of stop locations (or half a mile of high frequency transit)
	Anticipated transit delay due to stop location (In-lane stops and far-side stops typically reduce delay.)
	Presence or degree of transit priority treatments (where appropriate)
	Sidewalk width
	Proximity of marked street crossings to transit stop locations
	Average travel speed
Vehicular	Volume-to-capacity ratio
	Travel-time reliability
	Peak and off-peak travel time
	Estimated potential reduction in crashes using crash reduction factors
	Length of vehicle queues
	Average or 85th percentile travel speed
Freight	Volume-to-capacity ratio
	Travel-time reliability
	Peak and off-peak travel time
	Ability to serve freight origins and destinations
	Availability of loading zones
	Average and 85th percentile travel speed

Table 10:List of MassDOT's complete streets performance measures by mode (Lovas et al., 2015)

Mode	Performance Measures
Pedestrian	Linear feet of new or reconstructed sidewalks
	Number of new or reconstructed curb ramps
	Number of new or repainted crosswalks
	Number and type of crosswalk and intersection improvements
Bicycle	Miles of new or restriped on-street bicycle facilities
Transit	Efficiency or reliability of transit vehicles on routes
	Change in percentage of transit stops with shelters
	Change in percentage of transit stops accessible via sidewalks and curb ramps
Auto	Vehicle Miles Traveled (VMT) or Single Occupancy Vehicle (SOV) trip reduction
	Auto Trips Generated (ATG)
	Decrease in rate of crashes, injuries, and fatalities by mode
Multimodal	Transportation mode shift: more people walking, bicycling, and taking transit
	Percentage completion of bicycle and pedestrian networks as envisioned by municipal plans
	Increase in Bicycle, Pedestrian, and Multimodal levels of service (LOS)
Other	Rate of children walking or bicycling to school
	Number of new street trees/percentage of streets with tree canopy
	Economic impacts in business districts
	Satisfaction levels as expressed on customer preference surveys
	Number of approved exemptions from municipal Complete Streets Policy

2.3.5 Conclusions

Our interviews with experts and a review of design documents and guidelines from four leading state transportation departments along with recent reports from NCHRP offer a snapshot of the "state of the practice" for multimodal design. Broadly speaking, relative to the past, best practice now eschews imposing a "one size, fits all" solution that focuses on optimizing for automobile travel time. Instead, multimodal practice leaders favor solutions tailored to a particular geographic and social context that balance the transportation interests of car drivers, truck drivers, pedestrians, cyclists, and transit users. Best practice solutions also consider other important social goals such as increased safety and reduced noise, air, and water pollution. This shift in emphasis from one performance measure (level of service as a proxy for travel time and reliability) to many performance measures adds complexity and time to project design.

To address this complexity, modern best practice engages a broader range of stakeholders in project design, considers a wider range of alternatives, and allows for more design flexibility to match a solution to its specific context and potentially deliver more value for the project dollar. Ideally, a multimodal design process employs a suite of performance measures that address the competing stakeholder interests involved in a solution and allow them to see the tradeoffs among competing goals. Unfortunately, the state of the practice has yet to develop clear guidance on the appropriate set of robust and cost-effective performance measures that a project designer should apply to a project of a given type. The development of standard approaches to the use of multimodal performance measures represents the growing edge of multimodal design practice

3 MisplacedWheels, A crowdsourcing tool for gathering micromobility parking infraction data: the results of two parking audit case studies in Seattle and Portland

Acknowledgement: This project was funded by C2SMART, and the work presented in this chapter is a continuation of the paper: Pathak, C., Arabkhedri, B., & MacKenzie, D. (2021). Crowd-sourcing Micro-mobility Parking Violation Reporting – User Interface Design Motivation and Analytical Opportunities from Data Collected. *Transportation Research Board 2021 Annual Meeting*, Washington, D.C.

3.1 Introduction and background

Micromobility services (i.e., an umbrella term for shared e-scooters and e-bikes) have become increasingly adopted across various cities in the U.S. and throughout the world. Micromobility companies may operate only bike, e-bikes, or e-scooter or operate a variety of them. Micromobiloty services could further be categorized into two groups: dock-based (meaning that there are several docks or hubs scattered around the city and all trips have to be ended only at those locations) and dockless (meaning the vehicles can be left almost anywhere and, on any sidewalk as long as they are parked correctly). These companies normally have a smartphone app that allows the user to unlock a bike or scooter through scanning a QR code on the devices.

Micromobility companies show a promising future having replaced short distance car trips and provided first and last mile solutions for transit users (INRIX, 2019). Nonetheless, the popularity that these vehicles have gained, while beneficial for increasing mobility, has brought upon safety, equity, accessibility, and parking issues that all need to be addressed. With the advent of dockless micromobility, there is not a requirement for users to end their trips in a bike or scooter hub, and they can end their trip almost anywhere as long as they

abide by the parking regulations set forth by the cities. However, anecdotal observations as well as peer reviewed research have found that the amount of micromobility parking infractions across various jurisdictions is non-trivial and needs serious addressing. A literature review of past studies (which consisted of both academic articles and reports by city agencies) regarding micromobility parking violations found that the percentage of vehicles which were not compliant with the rules ranged from 8% to 32.5% (median=16.1%) (Brown et al., 2020). Furthermore, the report found that the percentage of vehicles blocking ADA access ranged as high as 2.8% of the audited fleet (Brown et al., 2020). This shows that many residents are potentially not fully aware of parking regulations in their cities which leads to this high number of infractions (Brown et al., 2020).

Different jurisdictions and cities also have different rules from one another, which complicates matters particularly for those living in two neighbor jurisdictions or using these services in two different cities. Further, the rules could be as specific as “to not reduce the sidewalk pedestrian zone to under 6 ft” to as broad as “to not park on vegetation and plants”. A study which analyzed twelve policy dimensions (e.g. speed limit, parking rules, no. of operators, etc.) across 10 peer cities to Nashville, did however find numerous areas of consistency among the different policies (Janssen et al., 2020). This study complements prior work by focusing specifically on parking policies, systematically comparing parking rules across multiple cities in the US.

When the users cause parking issues, it is normally the companies’ responsibility to resolve them per the permits and contracts that they sign with the cities. However, these infractions may not get reported in the first place if there is not an easy tool for reporting. Jurisdictions sometimes do not have an effective way to get reports on these parking violations and to pass them on to the micromobility companies to resolve. One the other hand, there are

jurisdictions which use services such as a 311 service line, online reporting, or emailing the micromobility coordinator of the department, to get informed on these issues.

We suggest a solution by developing a web application called MisplacedWheels to crowdsource parking infraction data from residents and to also provide a tool for city officials or contractors to conduct audits of the micromobility companies. The researchers used anecdotal data from interviews with officials from five jurisdictions (including cities, an unincorporated county, and one large university campus), to understand what the needs of these various authorities are when they want to get reports on micromobility parking infractions. The researchers also identified the parking rules of seven west-coast and one east-coast cities (with different populations, geographies, and other attributes) by studying the permits that these various cities had with the micromobility companies. They suggested a system to rank the parking infractions from most to least severe based on a score of 1 to 10 (with 10 being the most severe and having higher priority). A “no infraction” option with severity zero was also added for cases where the vehicle was parked correctly since the tool was also purposed for conducting data audits and marking no-infraction cases. Once the app was developed, the researchers conducted two parking audit case studies in the cities of Portland and Seattle. The data from the case studies was very briefly analyzed in Pathak et al. (2021). However, the paper did not include a thorough analysis of the data as it was primarily a motivation for the development and introduction of the app. This chapter, in addition to introducing some of the motivations behind the study and briefly discussing some jurisdiction parking rules, further includes a thorough analysis of the collected data.

The data is cleaned and merged with other datasets such as city shapefiles, census tract demographics, socioeconomic attributes, and built environment data such as number of bike racks and bus stops. The data is aggregated on a census tract level and is fed to a linear

regression model to find any relationships between independent variables such as median income, number of bike racks and bus stops, and population density in a census tract, and the percentage of parking violations in each census tract. Other models also analyzed the relationships between the named attributes and the percentage of high severity violations (severity >= 7), the number of violations, and number of reports from each census tract (to control for any biases).

This chapter is organized as follows. First, a brief summary of the interviews with city officials is mentioned by highlighting essential attributes requested in the app before moving to an analysis of the parking infraction rules in eight cities. Then the data audit sampling plan for the case studies is described in the data collection section. Data cleaning methods are mentioned in the next section, and then we move to spatial analysis of the data with numerous maps to understand the geographical distribution and prepare for the modeling section. Finally, we discuss several models built to find relationships between census tract demographics and/or built environment characteristics with the parking infractions and highlight the results. Lastly, some conclusions are drawn and future directions are discussed.

3.2 Benchmarking micromobility infraction reporting tools and results from interviews with five jurisdictions

Before conducting interviews, 13 U.S. cities were benchmarked in the fall of 2019 to improve understanding of how each of them handled micromobility parking infractions in their jurisdictions. These cities were chosen as they all had active micromobility programs. There was no systematic method in choosing these cities; but, there was a slightly higher focus on Northwestern cities. The cities chosen were (in alphabetical order): Atlanta, Austin, Bellevue, Chicago, Dallas, Houston, Los Angeles, New York, Portland, San Francisco, Seattle, Spokane, and Washington D.C. Table 11 shows the results of this benchmarking.

In this not very large sample, it was found that nine cities suggested to directly contact the bicycle/scooter companies to report infraction cases, five asked to call a local 3-1-1 number, three asked to report to the city's transportation department through email or calling, two mentioned to use a web portal to report the issue, and lastly, four guided users to report cases with the city's mobile app. The apps for Los Angeles and Dallas were namely myLA311 and Dallas311, and while Los Angeles's app did have a specific section for reporting micromobility infractions, Dallas's app only had a general section which could be used for micromobility as well. Seattle's FindItFixIt app and Bellevue's app both had built-in sections for reporting micromobility infractions. Nevertheless, Table 11 shows that even though some cities offer multiple solutions, many of them still rely on users contacting the companies directly; in fact, seven out of the nine that suggest directly contacting the companies, identify this method as the quickest and most efficient way to resolve issues.

After the benchmarking, the authors conducted interviews of five jurisdictions, including three cities, one unincorporated county, and one large university campus, which all had their own permits with either one or various micromobility companies. These interviews were conducted in the winter of 2020 before the COVID-19 pandemic. The names of these jurisdictions are kept anonymous; however, we will mention that all of them were based in the Pacific Northwest Region of the United States. These jurisdictions were asked about a set of key data and features that they deem as necessary information to be collected from micromobility parking infraction reports, particularly, information that would be useful both for themselves and for the bikeshare and scootershare companies in order to better manage parking violations.

Even though they all used different ways for handling infraction reports, they all mentioned some key features which need to be collected. The results of these interviews are shown in

Table 12. The table does not specify which of the jurisdictions were cities, an unincorporated county, and a university campus; they are brought in no particular order to keep their anonymity. Admittedly, this is a small sample size and did not serve as an ultimate guide to what we should and should not collect in an infraction reporting app; nevertheless, it did help us narrow down some key features that would later be implemented in the application.

Geolocation, photo, QR code, description of the problem, and priority of the violation were all features that were pointed out by the jurisdictions. Other interesting notes from the interview included the use of QR codes to verify whether the same bike was moved to another location leading to another violation or if an issue is reported several times, making it a high priority. The "level of frustration" with the infraction was also mentioned as a separate attribute from the "priority" of the parking infraction. The level of frustration is inherently different from the priority since, for instance, the presence of a scooter on one's private property may highly frustrate them while the cities and vendors may not see that as a high priority and aim at resolving more urgent issues such as ADA access blockage.

Another important note brought up was that in areas with neighboring jurisdictions having different operating companies, people may sometimes not be aware of the exact boundaries and move bikes and scooters from one jurisdiction to another. Further, in a number of cases, parking complaints which are the responsibility of one jurisdiction entity end up getting reported to another. This situation is further aggravated as sometimes, 1) a certain company may be operating in one and not the other; and 2) different jurisdictions may have different regulations in their permits (i.e., a situation that may be deemed as an infraction in one, may not necessarily be an infraction in the other). As a result, these jurisdictions pointed out that a singular reporting app which is geo-sensitive and would automatically provide a list of company names and infractions based on the location would be a useful tool for them in

resolving these (not so very often) issues with neighbor jurisdictions.

Table 11: Method(s) used by 13 U.S. cities for resolving micromobility parking infractions

City	Directly contact company	3-1-1	Email or call transportation department	Web-portal feedback tool	Mobile application
Atlanta, GA	❖				
Chicago, IL	❖				
New York City, NY	❖				
Portland, OR	❖		❖		
Washington, DC	❖		❖		
Bellevue, WA	❖		❖	❖	❖
San Francisco, CA	❖	❖		❖	
Houston, TX	❖	❖			
Dallas, TX	❖	❖			❖
Seattle, WA		❖		❖	❖
Los Angeles, CA		❖			❖
Austin, TX		❖			
Spokane, WA		❖			
Total Count	9	7	3	3	4

Table 12: The results of interviews with five jurisdictions specifying key and good-to-have features that they require a micromobility infraction reporter tool to incorporate

Suggested parking infraction attribute	Jurisdction A	Jurisdction B	Jurisdction C	Jurisdction D	Jurisdction E
Timestamp	✓	✓	✓		
Geolocation	✓	✓	✓		
Photo	✣	✓	✓		
Device ID (QR code)	✣	✓			✓
Company	✓				
Description of problem	✣		✓	✓	
Level of frustration			✣		
Priority of violation	✓		✓		✓
Send confirmation once issue is resolved				✣	

✓ Features that the jurisdictions want
✣ Additional good-to-have features

3.3 Review of parking infraction rules in various cities

This section reviews parking regulations across seven different, various-sized cities. Six of the jurisdictions are west-coast cities with five being in the pacific northwest (Seattle, Redmond, and Spokane in Washington, Portland, OR, and Boise, ID) and two in California (San Francisco and Los Angeles), and one on the east-coast (Washington D.C.). These cities were chosen as we initially had plans to conduct some scale of data collection in all of them and needed to implement the city-specific rules into our developed app for them. As we had collected all their rules, we sought this as an opportunity to group these rules into several categories in this section and understand to what degree these rules are similar or different.

The results can be seen in Table 13. Nine categories were defined and are as follows: 1) Sidewalk related, 2) ADA (rules in accordance to the Americans with Disabilities Act), 3) Blocking access, 4) Fastened to a street feature, 5) Rules related to the curb zone, 6) Rules related to emergency and utility facilities, 7) General no-parking areas, 8) Unauthorized parking areas, 9) Rules specific to a particular city. Our findings showed that parking regulations were to some extent similar for these different cities while some unique infraction rules were observed for cities like Portland, San Francisco, and Washington D.C.

We will start those that are similar. All cities had a rule which does not allow to reduce the pedestrian clear zone of the sidewalk to under five or six feet. Additionally, some ban parking in a sidewalk where the furniture zone is under three feet. They all had a rule that the scooters should not be toppled and should be parked upright (we categorized this as sidewalk-related). All cities banned vehicles from blocking access to ramps, doorways, entryways, travel lanes, bicycle lanes, and dedicated transit lanes (ADA related). Further, all of them disallow parking in a transit platform. They all do not allow bikes or scooters to be parked in someone's

private property and most of them ban these vehicles from being parked in planted areas or landscaping.

Most of them do not allow scooters to be placed next to street features or fastened to them. While some cities such as Portland and Washington D.C. do not allow scooters to be fastened to bike corrals, in D.C. it is required that shared bikes be locked to legal street infrastructure. Most cities have some sort of restriction for not parking in a geofence-restricted parking zone and restrictions for bikes or scooters being parked in one location for more than certain consecutive days (1, 5 or 7). However, Portland and Seattle have more specific rules such as not allowing scooters to be gathered in a cluster with more than 10 ft. of length and not having 15 or more devices in a 1000 ft. block face.

These infraction rules were also given a severity level from 1 to 10, with 1 being the least severe and having less priority, and 10 being the most severe and needing immediate resolving. Cities can adjust these severities on their own based on what they identify as higher priority for their operations. A list of the separate rules for each of the eight cities is also available in Appendix A.

Table 13: List of parking infractions for different cities grouped into 9 categories (SEA = Seattle, PDX = Portland, SF = San Francisco, LA = Los Angeles, DC = Washington D.C.)

No.	Category	Parking Regulation	SEA	PDX	Redmond	Boise	Spokane	SF	LA	DC	Severity
1	Sidewalk	Reducing pedestrian clear zone to under 5 or 6 ft.	✓	✓	✓	✓	✓	✓	✓	✓	10
2		Parked in the pedestrian zone or not parked in the furniture zone of sidewalk	✓							✓	8
3		In the corner of two intersecting sidewalks or near corner curb ramp	✓	✓			✓	✓	✓		8
4		In a block where furniture zone is under 3 ft. or on a block without a sidewalk				✓	✓	✓	✓		7
5		Toppled / Not parked upright	✓	✓	✓	✓	✓	✓	✓	✓	1
6	ADA	Blocking or within 5 ft. of ADA ramps and acommodations		✓		✓	✓		✓	✓	10
7		In or along a disabled parking zone		✓				✓	✓		9
8	Blocking access	Blocking access to ramps, doorways, or building entryways	✓		✓	✓	✓	✓			9
9		Blocking vehicular travel in a travel, bicycle, or dedicated transit lane	✓	✓	✓	✓	✓	✓	✓	✓	8
10		Near or blocking access to a driveway, alley, or curb cut		✓	✓	✓			✓	✓	8
11		Against building facades or in sidewalk café seating areas			✓			✓			8
12		Blocking access to a crosswalk	✓		✓			✓	✓		7
13		Blocking street features (e.g. benches, fire hydrants, etc.)	✓		✓	✓	✓				7
14		Blocking access to parked vehicles or in on-street parking spaces		✓		✓					5
15	Fastened to feature	Fastened to or blocking access to a bicycle rack		✓						✓	7
16		Fastened to street features (e.g. lights, signals, etc.)	✓	✓				✓	✓	✓	7
17	Curb zone	In a transit platform or within a certain distance of a transit sign	✓	✓	✓	✓	✓	✓	✓	✓	6
18		Within 5 ft. of a loading or taxi zone	✓	✓		✓	✓	✓	✓		6
19		In or along a red curb zone							✓		6
20	Emergency/Utility	Within 5 ft. of fire hydrant		✓				✓			6
21		Interfering with utility facilities (e.g. pipes, electrical cables, manhole covers)		✓							2
22	No-parking areas	In a geofence-restricted parking zone or bike/scooter no-parking area	✓		✓	✓			✓		4
23		Bike/scooter in one location more than certain consecutive days (1, 5, or 7 d)			7 d	1 d	7 d	7 d	5 d	5 d	2
24	Unauthorized area	In a traffic island, median, or traffic circle		✓							4
25		Within city parks, government property (Seattle only), or pedestrian plazas	✓	✓							3
26		In private property	✓	✓	✓		✓		✓	✓	3
27		In planted areas or landscaping (e.g. flowers/trees)	✓	✓		✓	✓		✓		2
28	Specific city rule	On a moving bridge or rail line crossing	✓								9
29		15 or more devices available in a 1000 ft. block face	✓								2
30		Scooters are in a cluster with more than 10 ft. length or two scooter clusters placed within 20 ft. of each oter		✓							1
31		More than two scooters in one bike rack or scooter locked to another vehicle						✓			3
32		Bikes not locked to legal street infrastructure								✓	4

3.4 App development

Our research team developed a mobile web application called MisplacedWheels throughout the winter and spring of 2020. Since it is a web-app, it means that it operates on any browser on almost any phone as it does not depend on the OS of the device. The user interface of the app has three essential steps for reporting a mis-parked vehicle: location, classification, and identification. In the first step, the user can pin the location of the mis-parked vehicle on a map or use the smartphone's GPS to find the location. In the second step, the user classifies the type of infraction by selecting one or several items from a list of infraction rules and selects the company of the vehicle. In the last step, the user can identify a specific vehicle by scanning the QR code. Further, step 2 also enables the user to upload a photo of the mis-parked vehicle. The details of the app development are mentioned in Pathak et al. (2021). Some screenshots of the app are brought in Figure 9.

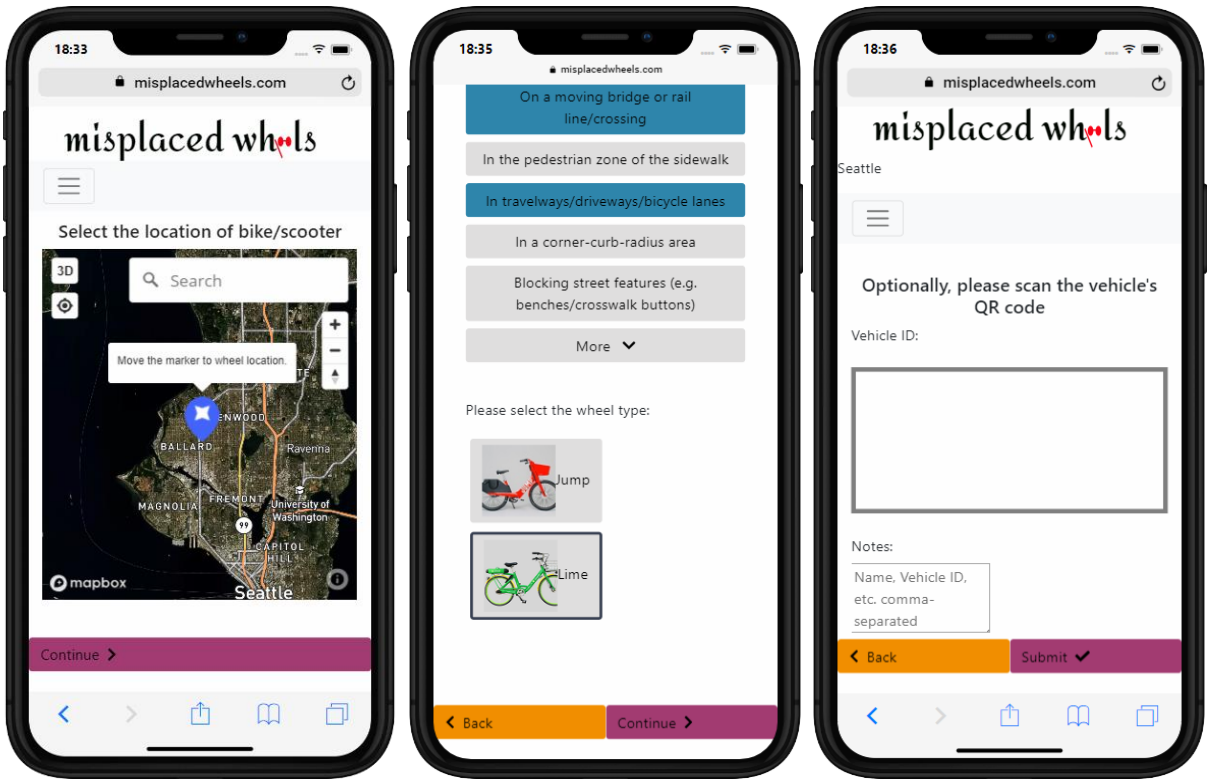

Figure 9: From left to right (a) location page, (b) classification page, and (c) identification page of MisplacedWheels.com (Pathak et al., 2021)

The list of infractions and micromobility companies are sensitive to the city. The parking infractions and companies of eight cities are implemented in the app all previously named in Table 13, thus the rules in the app are in accordance with the government's requirements for parking in those cities. The order of the list of infractions is sorted by severity with higher infractions shown on top and lower ones shown in the bottom.

3.5 Data audit conceptualization and sampling plan

One purpose of our research team after developing the app was to partner with other cities and offer them this service so that it could enhance their micromobility management system and serve as a data solution for their current lack of information regarding micromobility mis-parking. From our viewpoint, such a resource could not only help them resolve parking issues quickly and efficiently but also to help understand parking infraction hotspots in the long-term. However, due to the spread of the COVID-19 pandemic in early 2020, micromobility ridership dropped severely per the stay-at-home orders and many micromobility operations were disrupted. Thus, our initial goal of partnering with cities and collecting data through large volumes of crowdsourcing was not accomplished. Nevertheless, we sought the opportunity to conduct a data audit ourselves to be able to answer some of our research questions.

A data audit of the parking situation was performed by the research team in the cities of Seattle and Portland. Seattle was chosen due to the researcher living in the area and easy access for the author to conduct a data audit. Portland was chosen due to its proximity to Seattle and also because it was representative of more micromobility companies (five companies at that time). Data was collected for four days in Portland from July 18th to 21st of 2020, and for two days in Seattle from July 22nd to 23rd of 2020.

Seattle, at the time, had only about 200 electric bicycles in its boundaries. All the e-bikes were for the company JUMP. This was before the introduction of several new scooter companies that arrived in the city around September and October of 2020 (i.e., LINK, Wheels, and Lime, along with the previous JUMP bikes). Portland, on the other hand, was a bigger hub for micromobility vehicles at the time, compared to Seattle, and all of its micromobility companies operated e-scooters. In terms of sheer number of micromobility vehicles, there were around six times more e-scooters in Portland at that time compared to Seattle's roughly 180 e-bikes.

To locate and find the number of scooters available across both cities before and during the audit, an app named ScooterMap was identified and used by the authors as a primary source (Pontis, n.d.). This app contained information on all scooters and bikes that show up on the map by pulling data from the micromobility companies' APIs. This app was used both prior to the study, for counting the number of micromobility vehicles in each city and preparing a sampling plan, as well as during the study, for finding the vehicles' locations. Figure 10 shows a screenshot of the Scooter Map app and its user interface. The pins on the map display where the micromobility vehicles are parked, with the logo of the company being shown on the left-side of the pin and the type of the micromobility vehicle (bike or scooter) on the right-side. The colors of the pins indicate the battery level of the vehicles with red being the lowest, green being the highest, and yellow in between (the thresholds are not known). As of June 2021, when this thesis was written, the app is no longer available.

For the City of Seattle, the author collected data by doing an audit of all scooters that showed on the map. As there were only about 180 e-bike available in the city (according to ScooterMap), it was easily possible to audit all the bikes in two-days' time. For the City of Portland, however, a sampling plan was prepared to sample roughly half of the scooters there

since it had a much larger number compared to Seattle. The sampling method for Portland is mentioned in the following subsection.

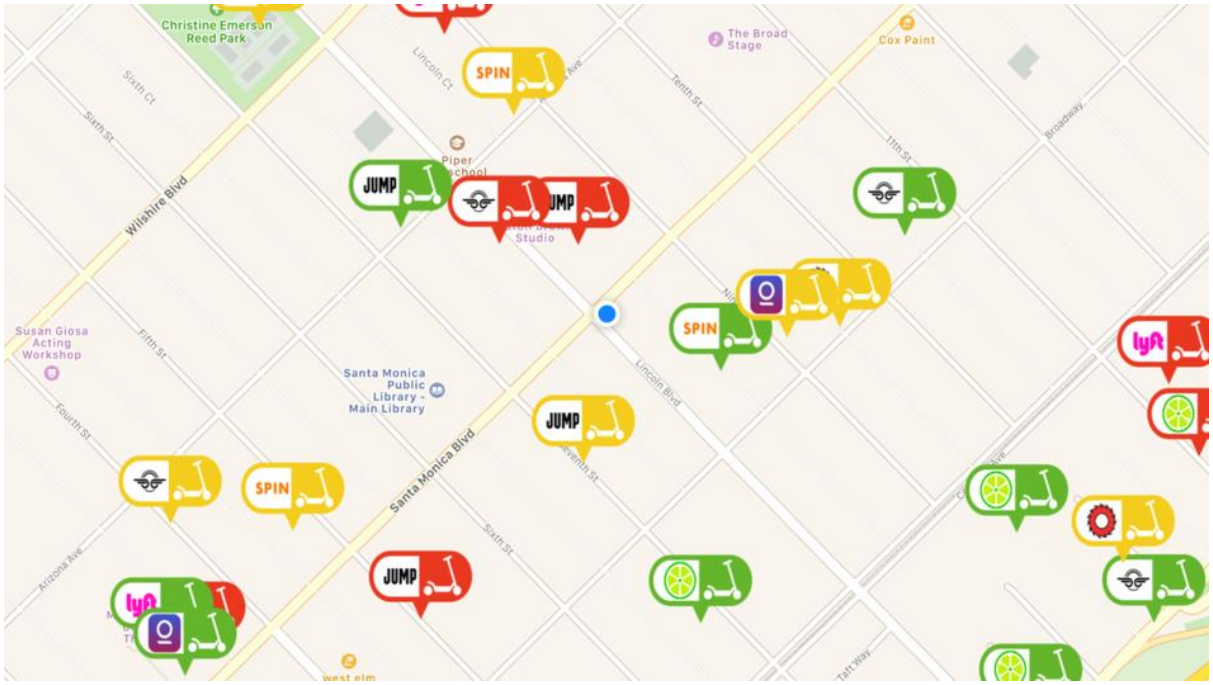

Figure 10: The user interface of Scooter Map (Lekach, n.d.)

3.5.1 Sampling method for Portland

There were about 1160 scooters in the city of Portland according to Scooter Map (Pontis, n.d.) on 7/15/2020, three days before the data collection. As this is a relatively large number, a census of all the micromobility vehicles was not possible to carry out, and thus we had to sample a limited number. Therefore, a data sampling plan was gathered in preparation for the data collection.

We wanted to sample about half of the total number of scooters in the city, meaning around 600 scooters. Having done smaller-scale tests of the app before, we established that each report submission in the app would roughly take 30 seconds, an attribute that can also become faster as the user gets comfortable with the app. Also, traveling between every two

scooters was assumed to take around 3.5 minutes, accounting for the walking and driving of the auditor, within and between neighborhoods. As a result, it was assumed that 60/4=15 scooter reports can be submitted per hour. By taking into account 10 hours of auditing per day (excluding lunchtime and rests), this would add up to 150 scooters per day. Thus the sample of 600 scooters could be achieved in four days of data collection.

Cluster sampling was proposed as the sampling method. In cluster sampling, the entire data frame is divided into several disjoint clusters. Zip codes, census tracts, and census block groups are all popular for achieving different scales in cluster sampling. However, based on our scale of data collection (citywide scale), zip codes were ultimately chosen as a suitable disjoint cluster for this study.

According to the City of Portland's official website, Portland has 32 zip codes. However, a number of these zip codes are only partly within city boundaries (i.e., a very large portion of the zip code's area is outside city boundaries, for example, more than 90% of the area) or are suburban areas with scooters being virtually or entirely non-existent in them according to Scooter Map. After excluding such areas and using Scooter Map to find zip codes with at least 20 scooters, a total of 16 zip codes were identified as viable clusters, shown in Figure 11.

Having divided the entire frame into 16 disjoint viable zip code clusters, we then wanted to select a random sample of eight clusters (half of the total cluster). Using Scooter Map's real-time data, we had a rough estimate of the number of scooters available for rent in each of the zip codes. It is said rough, and not exact, because scooters may constantly change locations as scooter users move them from one neighborhood to another; nevertheless, it was assumed that chronological changes in the number of scooters per zip code are not major. We wanted

to ensure that the sum of scooters in the eight random clusters would result in our overall achievable number of 600 scooters for the four-day data collection.

The sampling process was (admittedly) not entirely random due to not accepting the first random few samples since they did not result in a number of around 600. However, it only took a few random tries until the setup of the eight sampled corridors reached an overall number of around 600. This meant a slightly higher concentration in urban and central areas to achieve higher scooter numbers. The selected clusters are shown in Figure 12. Further, Figure 13 shows the actual collected data overlaid on the same map to show that the data collection was in accordance with the sampling plan.

In addition to those scooters which showed up on Scooter Map, several other scooters that were not available for rent in the app were also identified when the auditor was walking in various neighborhoods. These scooters did not show on scooter map because they were disconnected from the API; nevertheless, they were collected in our data collection leading to the larger number of samples than what we expected (around 690 instead of 600). In addition, there were a near-total of 20 scooters (out of the 690 scooters audited) that were in a neighboring zip codes but very close to the zip code boundary. Even though these were not within the boundaries of the eight zip codes they were collected by the researcher. Lastly, the reason why it took four days to collect 690 data points in Portland and two days to collect nearly 160 data points in Seattle goes back to the fact that scooters in Seattle were more geographically dispersed. The data audit involved less walking and mostly driving between neighborhoods, causing a higher travel time between every two scooters.

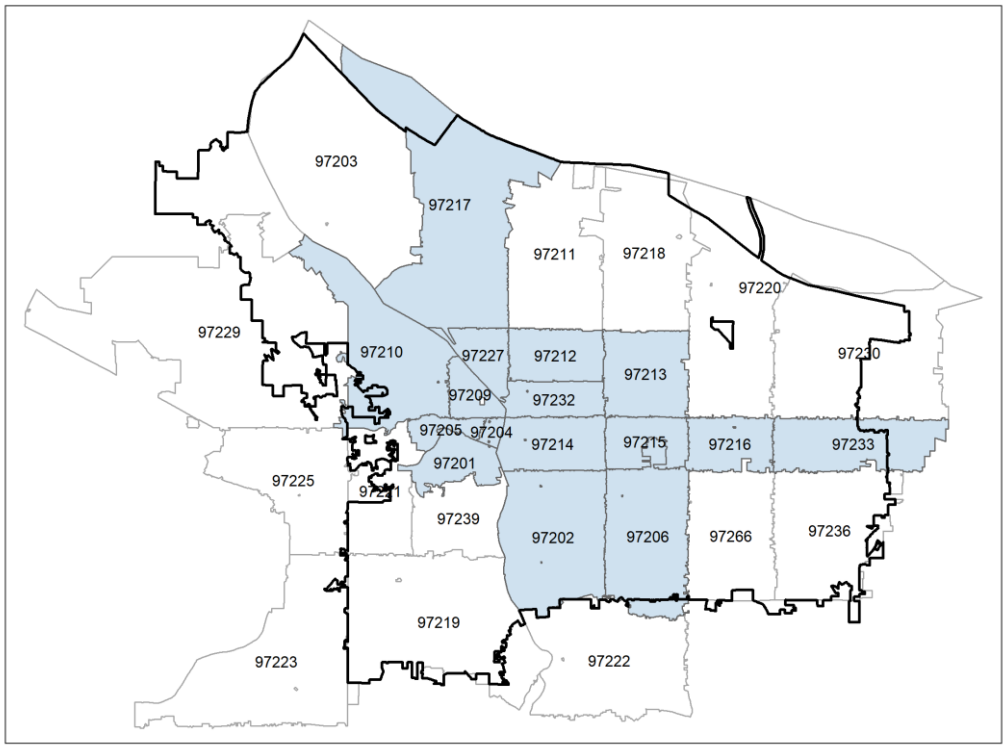

Figure 11: Zip codes with at least 20 scooters shown with a light blue shade. Thick border depicts Portland's boundaries.

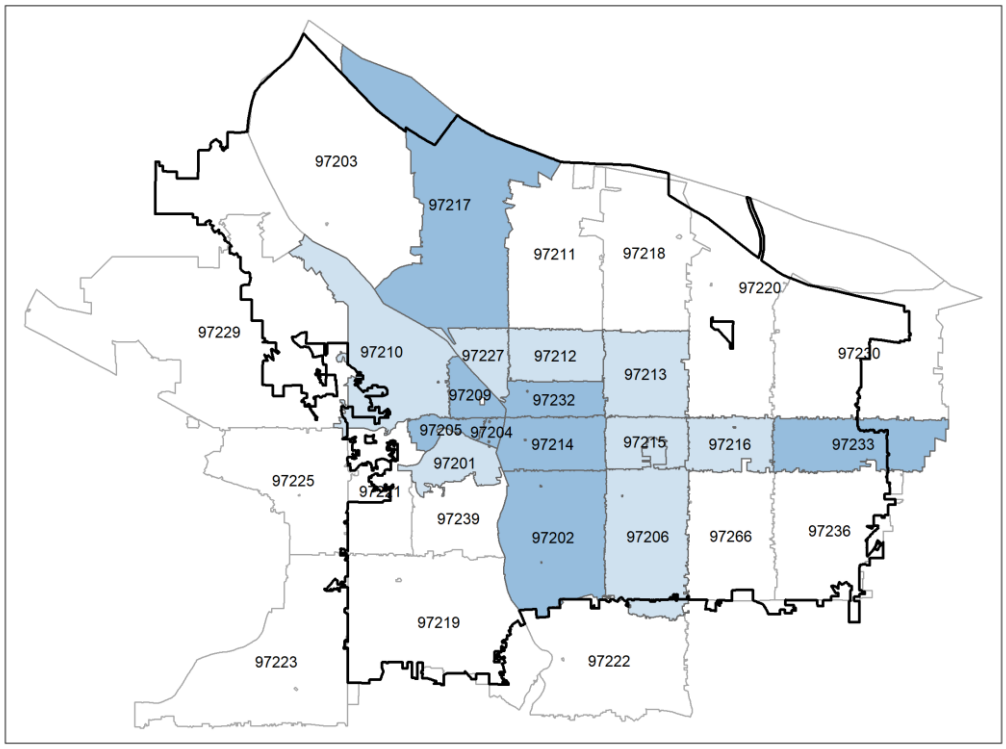

Figure 12: Eight randomly sampled zip codes, shown in a darker shade of blue, that will be used as the disjoint clusters for the study

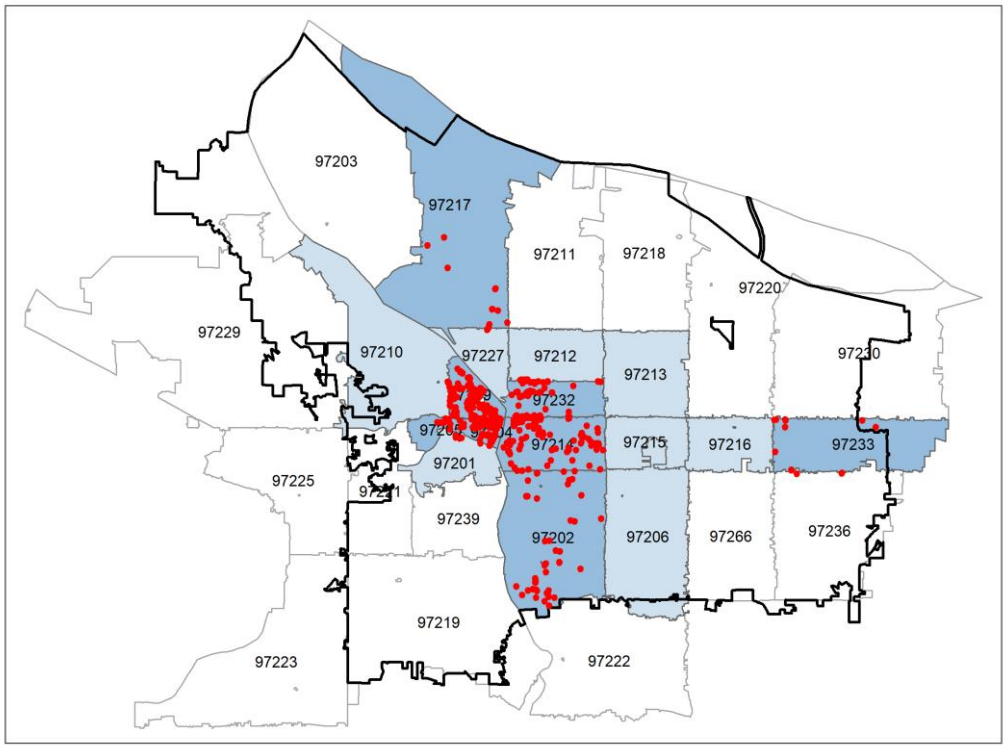

Figure 13: The actual collected data overlaid on the zip code map after the data collection. The map shows that all collected points are in accordance with the sampling plan as they are within the dark blue shade.

3.6 Data cleaning, post-processing, and summary statistics

After data collection, the data was post-processed in R language (R Core Team, 2021) to achieve the following three goals: 1) to clean any duplicate or unrelated data, 2) create summary statistics, 3) to spatially plot and analyze the data, 4) join the dataset with other resources such as socioeconomic and demographic info from the census and data from the built environment such as number of bus stops, bike racks, etc. to model the data.

3.6.1 Data cleaning and post-processing

There was not an intense amount of cleaning needed after the data collection. Base R libraries and the dplyr package were used for all the cleaning purposes. First, as was seen in Figure 13, there were two points in the eastside 97233 zip code that laid slightly outside of Portland's

boundaries in the City of Gresham. Those two points were yet included for Portland and not removed even though they were in a neighboring city. Another data cleaning task was to ensure that all reports had a single company listed as their company label. The auditor made sure, during the data collection, that he submits an individual report for each scooter, even if they were only several inches away from each other. Nevertheless, there was one case where two scooters from different companies were reported in one report with two company labels. Thus, two individual reports were created for that single report during post-processing, and the original report was removed. Lastly, for the case of Seattle, the University of Washington (UW) had a different set of rules from the city and had its own permit with JUMP and ran autonomously from Seattle's jurisdiction. We had also incorporated UW's rules within its boundaries and geo-referenced it into the app. Thus, during the two-day Seattle data collection, there were 12 reports generated from within UW's jurisdiction that are not brought in this thesis. With those being removed, 156 reports were submitted all under Seattle's jurisdiction, and 690 reports for Portland. Other than these named tasks, no further data cleaning was needed.

Figure 14 shows the total number of reports from each city by breaking them into violation and non-violation categories. It was found that out of the 690 vehicles audited in Portland, 292 were in violation of the city's rules (0.42 violation rate), and out of the 156 vehicles audited in Seattle, 95 cases of violations were seen (0.61 violation rate). Portland seems to be better off compared to Seattle in terms of the violation rate. A two-tailed hypothesis test was performed to see if there is a significant difference in the portion of violations between the two cities. The null hypothesis was that there is no difference between the two cities, and the alternative was that there is a difference. Before testing, we looked over the conditions for inference meaning to make sure both samples were random, normal, and independent. The sample from Portland was taken through random cluster sampling so it does somewhat meet

the condition of randomness, however, for Seattle, the entire population of scooters was studied. Even though this means the conditions of inference are not met, the hypothesis test was still performed. α=0.05 was assumed.

$$H_0\text{: } p_{seattle} = p_{portland} \tag{1}$$

$$H_0\text{: } p_{seattle} \neq p_{portland} \tag{2}$$

$$p_{seattle} = \frac{95}{156} = 0.6090 \tag{3}$$

$$p_{portland} = \frac{292}{690} = 0.4232 \tag{4}$$

$$p_c = \frac{95 + 292}{156 + 690} = 0.4575 \tag{5}$$

$$\begin{aligned} \sigma_{p_{seattle} - p_{portland}} &= \sqrt{\frac{0.4575 \times 0.5425}{156} + \frac{0.4575 \times 0.542}{690}} \\ &= 0.0442 \end{aligned} \tag{6}$$

$$z = \frac{p_{seattle} - p_{portland}}{\sigma_{p_{seattle} - p_{portland}}} = \frac{0.6090 - 0.4232}{0.0442} = 4.21 \tag{7}$$

$$p - value = 0.000026 \leq \alpha = 0.05 \tag{8}$$

According to Equations 1 to 8, it was found the null hypothesis can be rejected, and the difference between the rate of parking violations in Seattle and Portland is significant. However, again, this test may not entirely meet the conditions of inference as the data for Seattle is not a sample and is the entire number of shared e-bikes in Seattle.

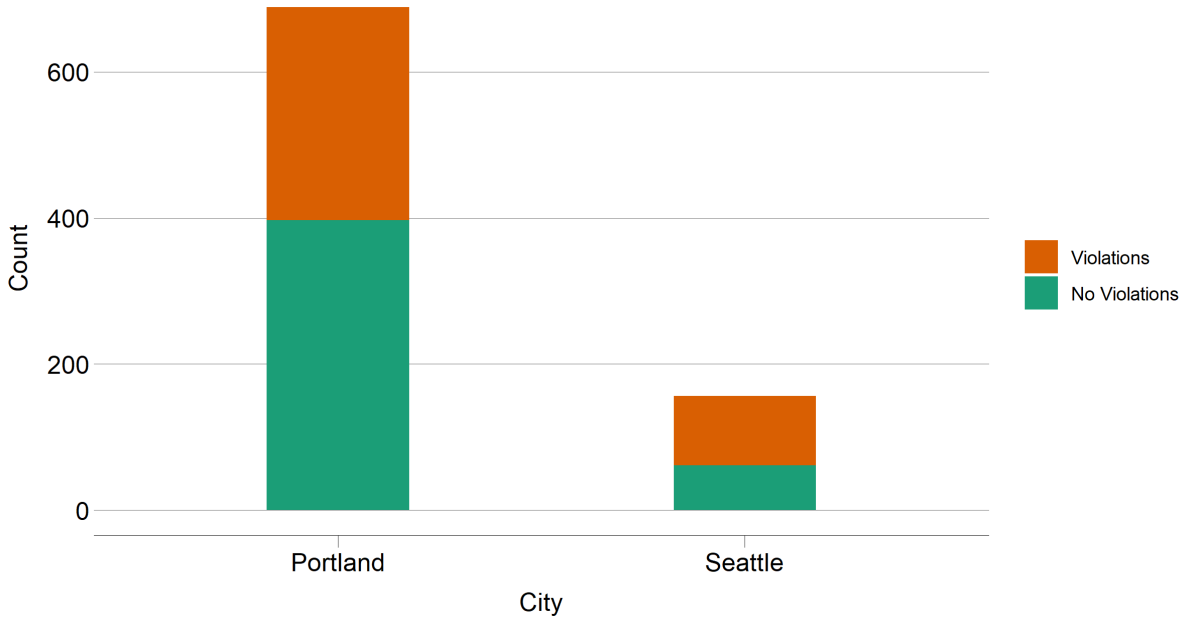

Figure 14: The number of violation and non-violation reports stacked on top of each other for Portland and Seattle. The height of the bar is the total number of reports for each city.

3.6.2 Summary statistics

Below are some summary statistics of the data to help understand them better. Figure 15 and 16 show the number of vehicles audited for each company, for Seattle and Portland, respectively. As it was mentioned, at the time of the data collection, only JUMP e-bikes had a permit and were available in the City of Seattle; however, there were also two Lime e-scooters observed in the audit. It was perceived that the scooters were moved from a nearby county to Seattle. Regardless, they were included in the count of the data. For Portland, Spin had the highest number of e-scooters in the city, followed by Lime, Bird, Bolt, and Razor.

Figures 17 and 18 then show the number of violations next to the total number of vehicles audited for each of the companies, in Seattle and Portland, respectively. Furthermore, Figures 19 and 20 display the portion of different severities for each of the companies, in Seattle and Portland, respectively. Severity 0 means no violation, and severities 1 through 10 all mean some sort of violations with 1 being the least serious, such as the vehicle being parked on

vegetation, and 10 being the most serious, such as vehicle reducing sidewalk width to under 6 ft. It can be seen that in Portland all of the companies have more than 50% of scooters without any violation (severity = 0), with Bird doing exceptionally well by having more than 75% of scooters not violating the rules. It was anecdotally observed during the data collection that Bird scooters were maintained better than others as they were mostly grouped together on the furniture zone of the sidewalk probably by a company worker, thus resulting in a lower violation rate. Regardless, all companies had more than 10% of scooters with a severity of 10 (meaning either blocking the sidewalk or causing an access issue for people with disabilities) with most of them having a rate near 20% or 25%.

Lastly, Figures 21 and 22, demonstrate the distribution of the violation severities (severity = 0, meaning non-violation, was excluded), for Seattle and Portland. Histograms and density plots were used for these figures. While there was a slight element of subjectivity blended into the severity rankings, the distribution plots are yet alarming due to their high numbers of severity 10 (mostly being reducing the sidewalk pedestrian clear zone to under 6 ft or causing an access issue for the disabled). Seattle, having a violation rate of 0.62, higher than that of Portland, has 35% of violations with severity of 1. Both cities have roughly 45% of violations with severity of 10. Seattle has a mean severity rate of 5.5 while Portland's is around 7.1. A hypothesis test was not performed to see if the difference is significant due to the element of subjectivity that was discussed.

After looking at the summary statistics, some spatial analysis of the data was conducted along with gathering census data for modeling data.

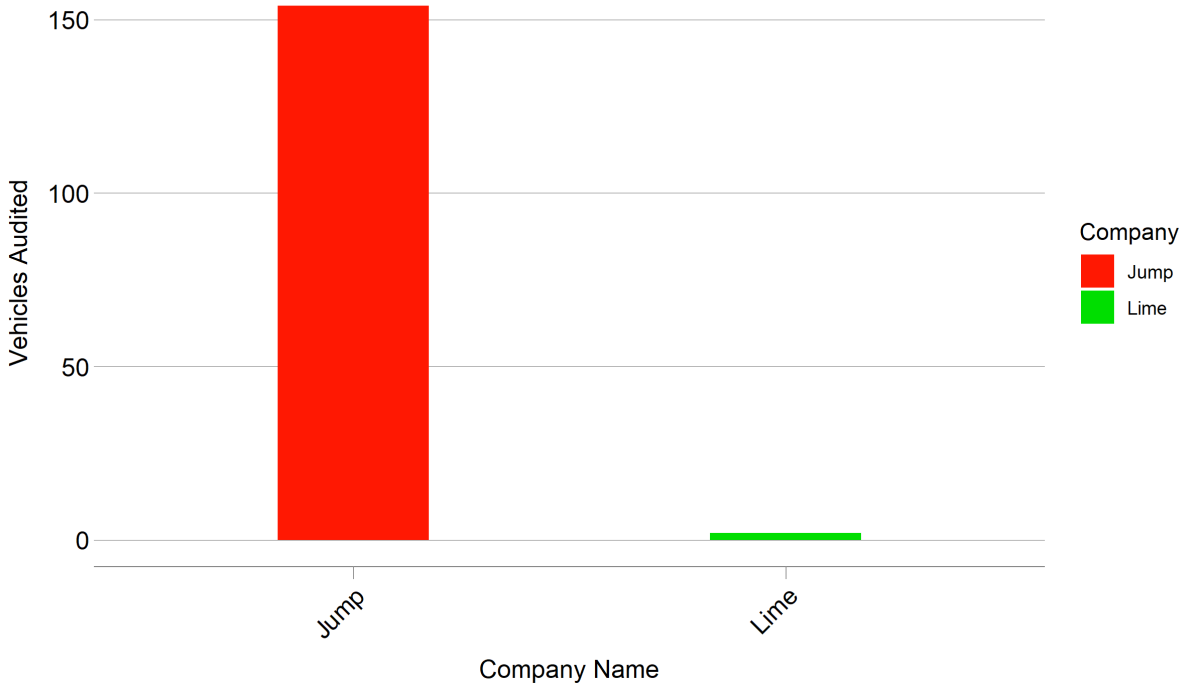

Figure 15: Count of micromobility vehicles audited in Seattle per scooter company operating there, color coded by the company's colors

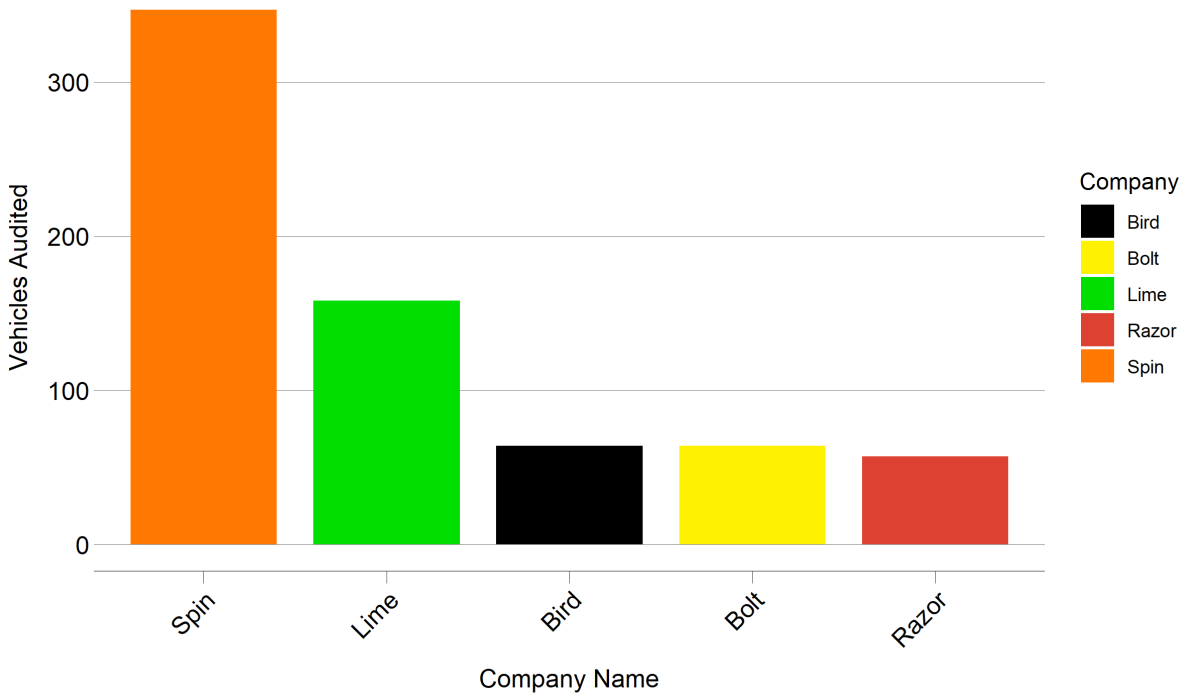

Figure 16: Count of micromobility vehicles audited in Portland per scooter company operating there, color coded by the company's colors

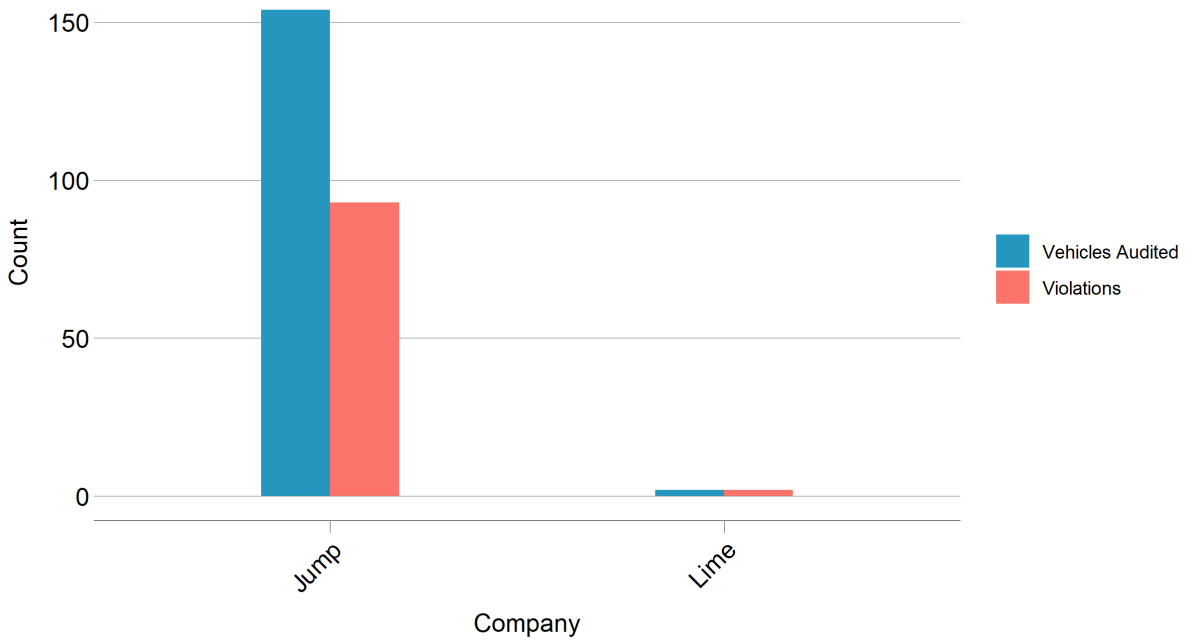

Figure 17: Number of vehicles audited, plotted next to the number of violations for each micromobility company in Seattle

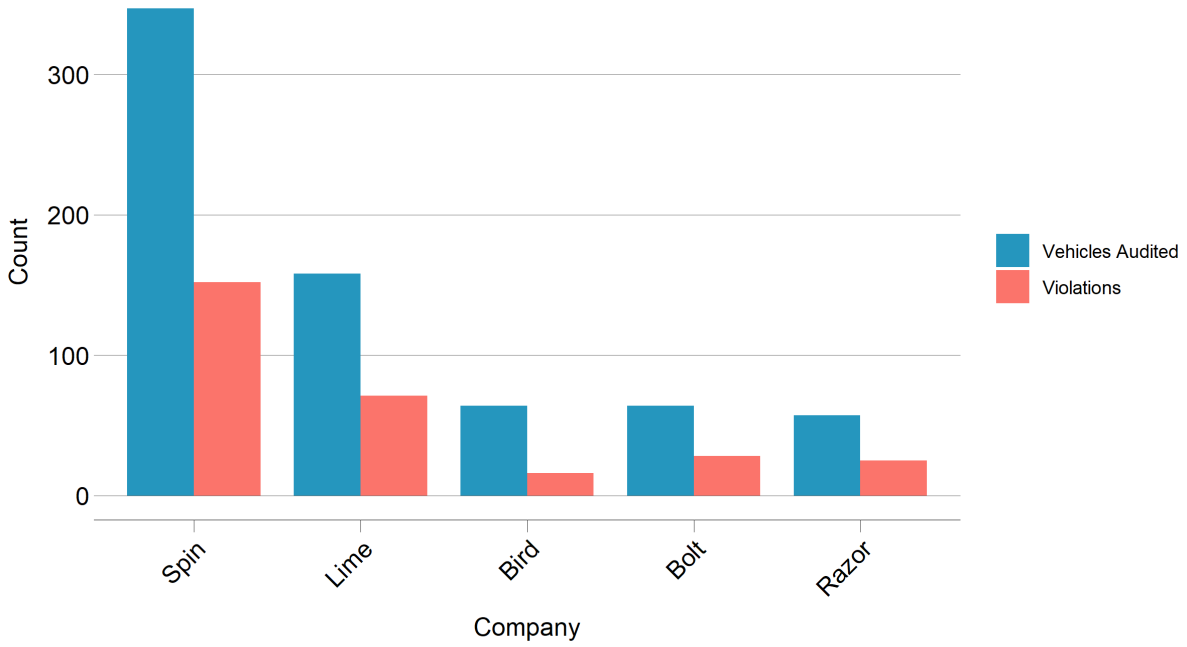

Figure 18: Number of vehicles audited, plotted next to the number of violations for each micromobility company in Portland

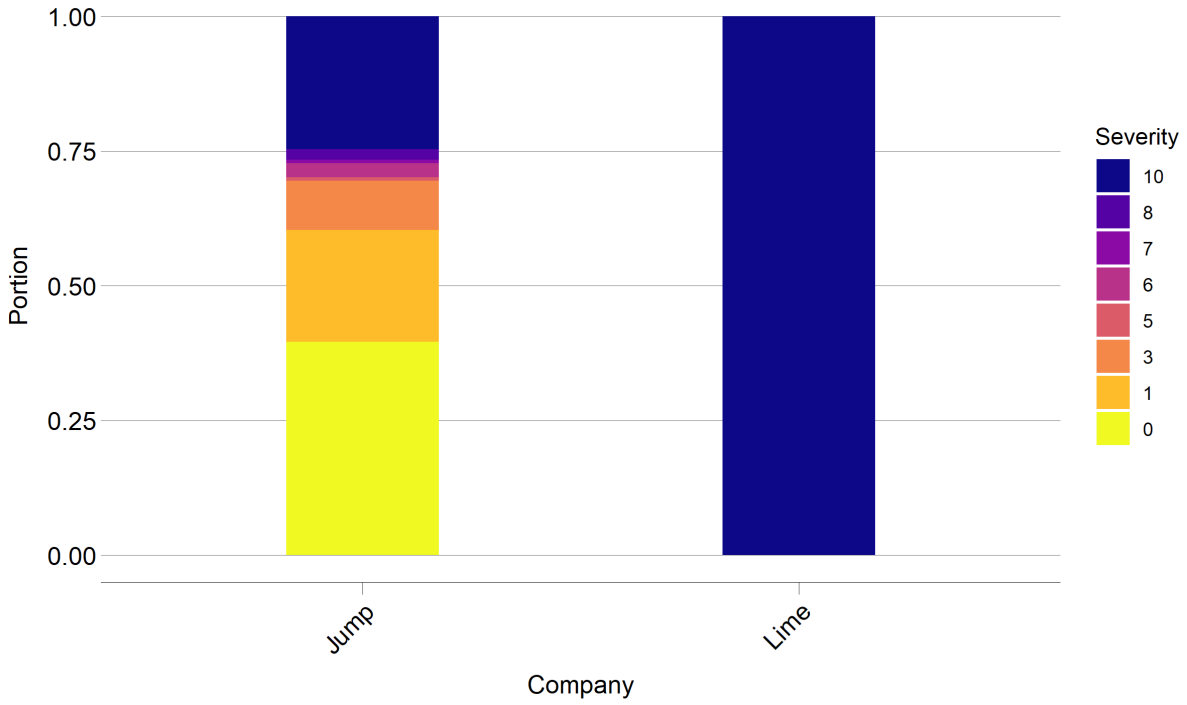

Figure 19: Portion of different severities from 0 (meaning no violation) to 10 (severities 1 through 10 all mean some sort of violations) for Seattle

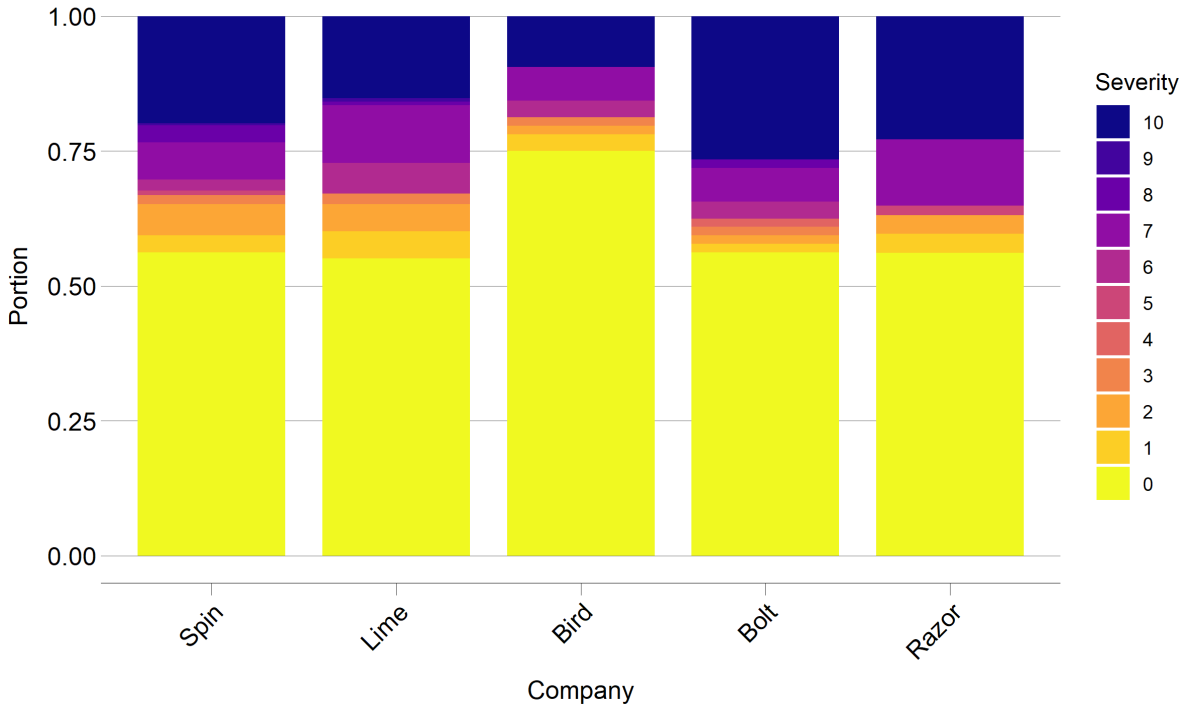

Figure 20: Portion of different severities from 0 to 10 for Portland

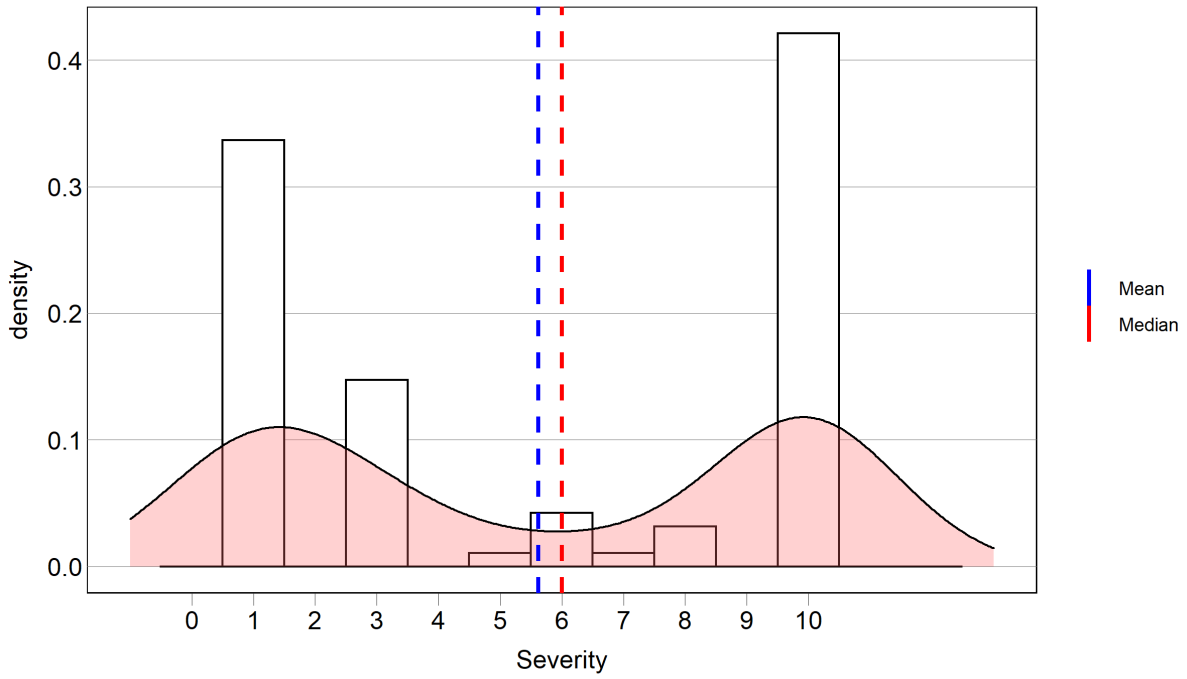

Figure 21: Histogram and density plot showing the severity distribution of violating micromobility vehicles in Seattle (severity 0 is not included)

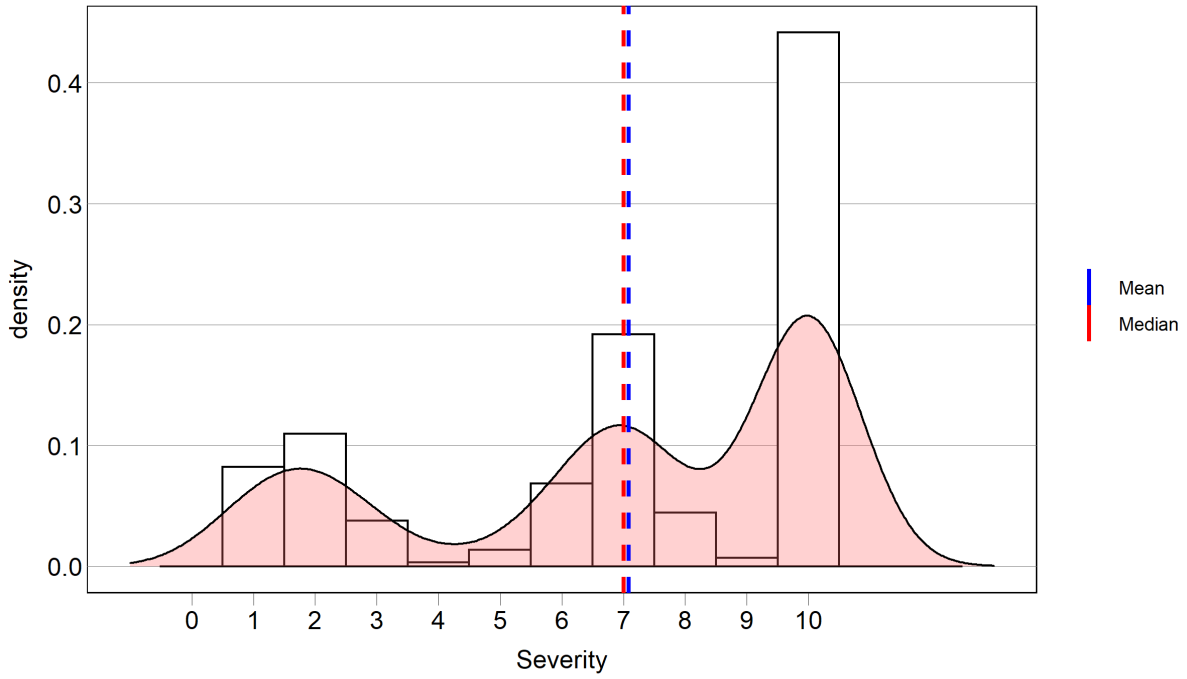

Figure 22: Histogram and density plot showing the severity distribution of violating micromobility vehicles in Portland (severity 0 is not included)

3.7 Spatial analysis

In this section, multiple attributes of the data are plotted across a variety of maps to better understand the distribution of the data. The severities of the violations are also shown through a heatmap, and the infraction situation across different census tracts is shown using an interactive plot. The distribution of transit stops and bike racks across the city are also overlayed on the infraction reports data to visually see if there are any correlations between these attributes.

Even though an interactive spatial analysis tool for the data is already available online at Misparkrepo.com (Pathak et al., 2020), the micromobility infraction manager tool which was developed by the team, this section is an effort to go beyond the tools already offered in Misparkrepo. We aim to particularly point out map aesthetics that may help in identifying infraction hotspots more effectively as well as another interactive tool which allows for aggregate neighborhood comparisons rather than seeing single infraction report spots.

The data was plotted in R using “tmap” (Tennekes, 2018) and “ggmap” (Kahle & Wickham, 2013) libraries. First, Figure 23, shows a heatmap of the severities for Portland while Figure 24 shows a zoomed-in version for Portland with a particular focus in Downtown and Central Portland areas. Figure 25, shows the same map type for Seattle. The choice of color for these figures is primarily important as it highlights those infractions with higher severity (in purple) while displaying the lower priority infractions in yellow. Further, an alpha parameter of 0.3 is set for the glyphs (circles) to allow for better transparency and visualization for points that overlay each other. This particularly helps to better monitor denser areas such as the case in Downtown Portland (Figure 24) where many reports are generated in very close blocks. Additionally, the glyph size also varies for different severities to bring more concentration to areas with higher severity. Many of these aesthetic points come from points discussed in a

data visualization course by Chris Adolph and from Edward Tufte's The Visual Display of Quantitative Information principles (Tufte, 1985).

Another data exploration opportunity sought was the visual display of aggregated census tract-level infraction rates. Infraction rate is defined as the number of vehicles in a census tract not compliant with rules, divided by the total number of audited vehicles in that census tract (i.e., number of violating vehicles / total number of audited vehicles, for each census tract). Furthermore, high severity infraction rate is defined as the number of vehicles in a census tract with a severity of higher than seven, divided by the total number of audited vehicles in that census tract.

These two metrics would allow for a comparison of how various census tracts are performing compared to one another. Figure 26 and 27 show the infractions rates and high severity infraction rates, respectively, for various census tracts in Seattle where data were collected from. Figure 28 and 29 show the same respective features for Portland. Figures 30 and 31 show the same but they are zoomed in to show Downtown and Central Portland areas as the number of reports are denser there. An interactive version of these maps is available for Seattle and Portland for parking infraction rates (Arabkhedri, 2021b) and high severity parking infraction rates (Arabkhedri, 2021a) per census tract.

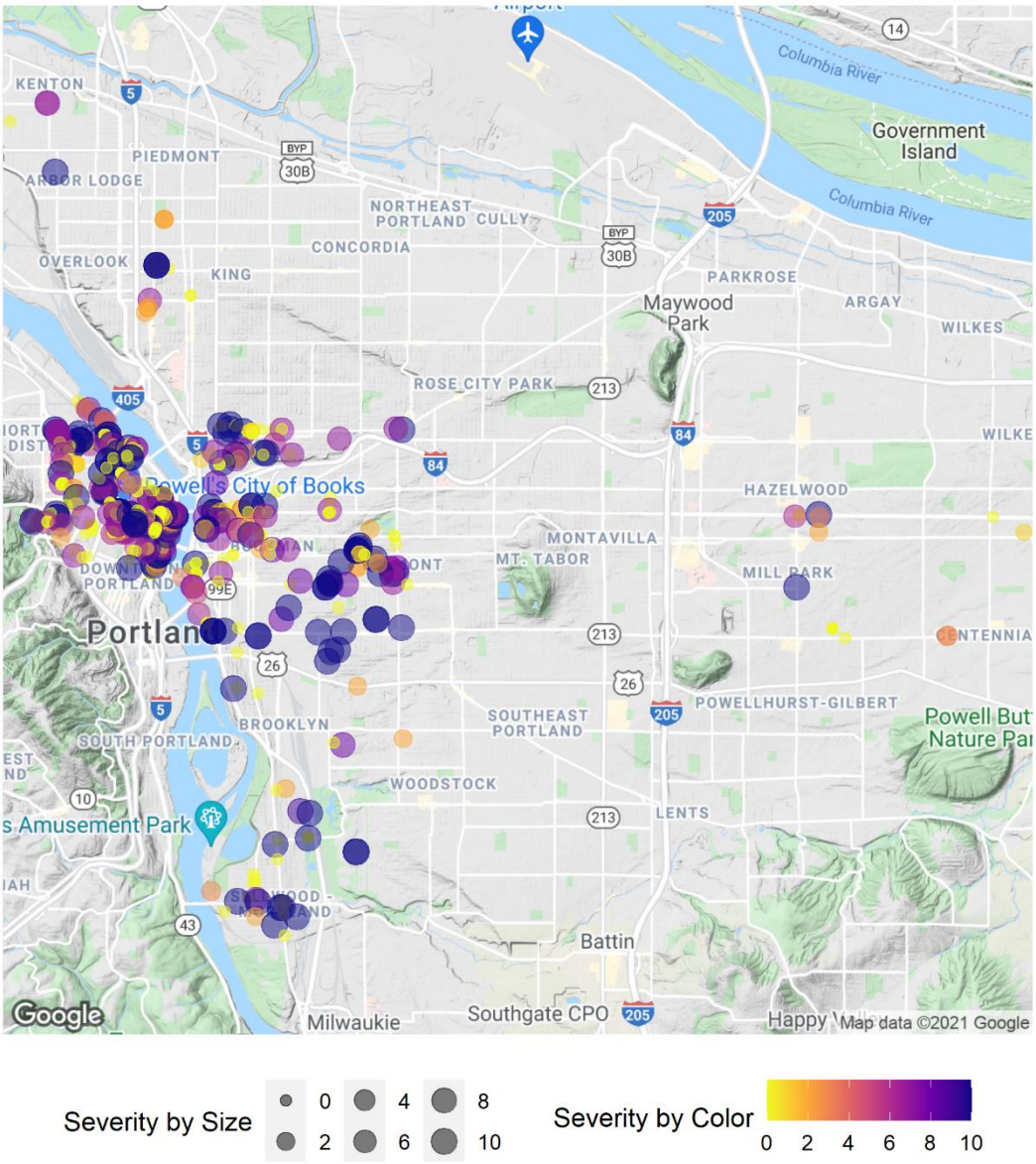

Figure 23: Distribution and severity of parking infraction reports in the Portland case study

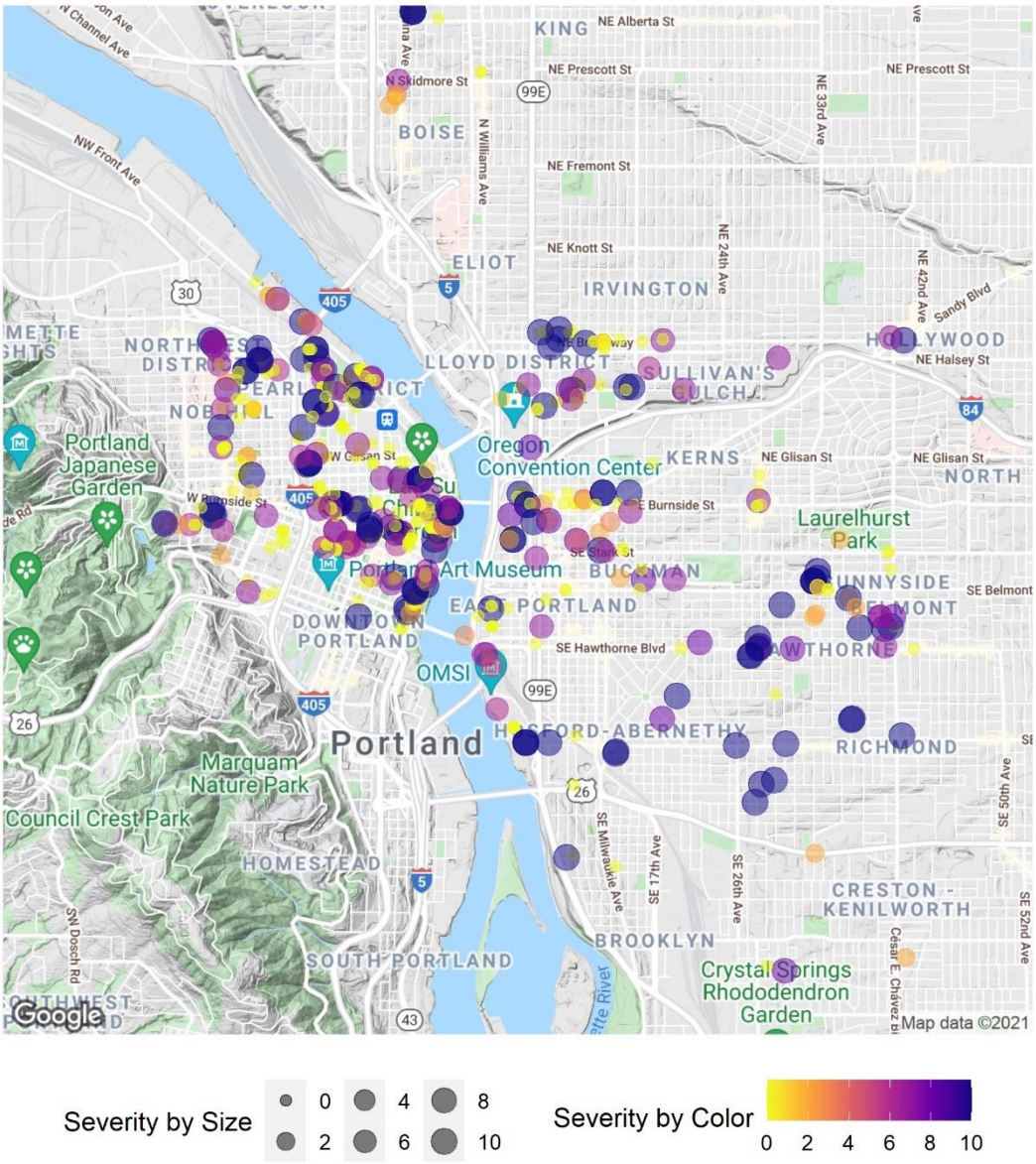

Figure 24: Distribution and severity of parking infraction reports zoomed in on Downtown and Central Portland areas for better visualization

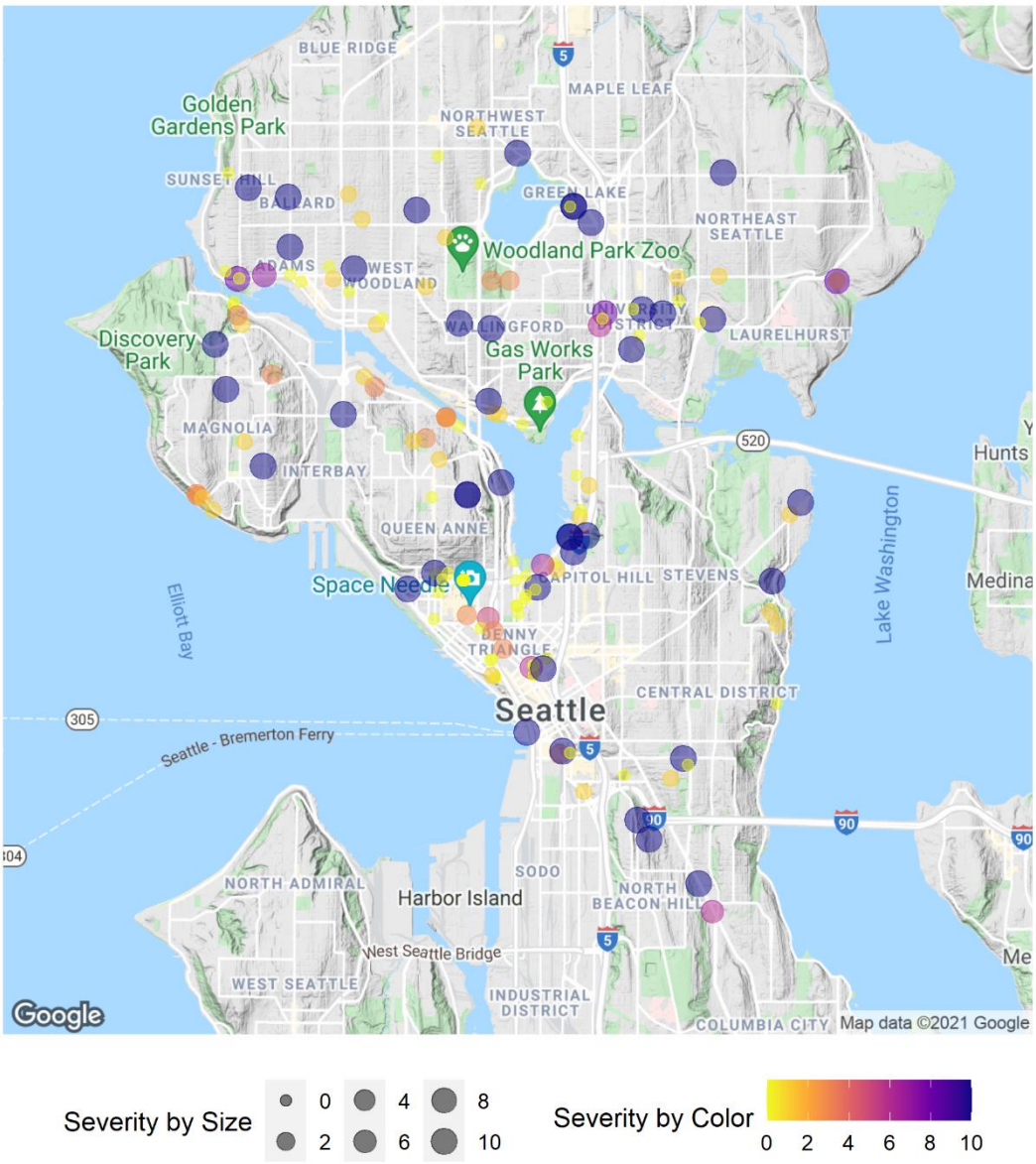

Figure 25: Distribution and severity of parking infraction reports in the Seattle case study

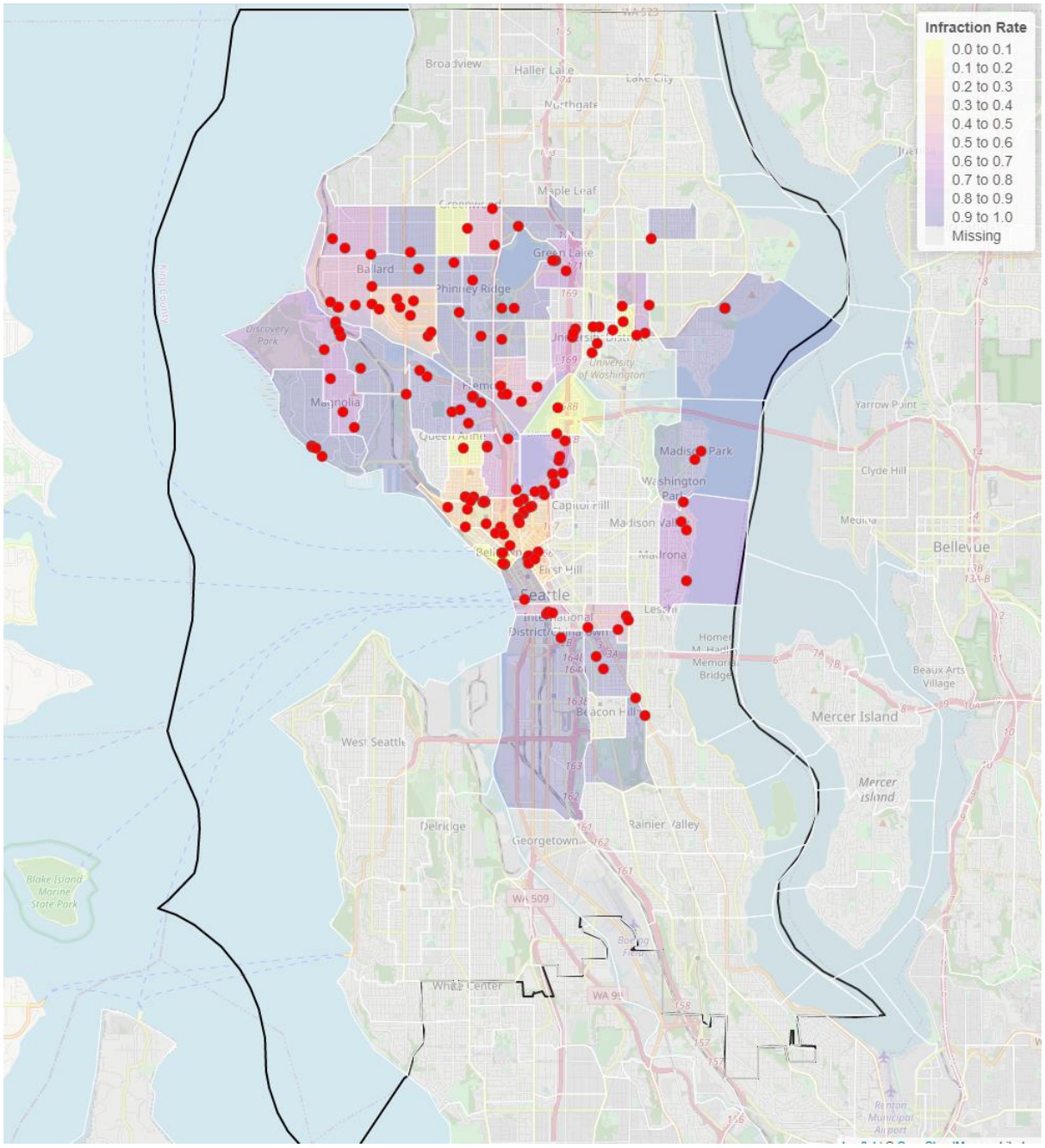

Figure 26: Micromobility parking infraction rates per census tract for the City of Seattle shown with different colors (purple for highest rate bin and yellow for lowest rate bin). Interactive version available at: https://rpubs.com/bornakhedri/micromobility-parking-infraction-rate

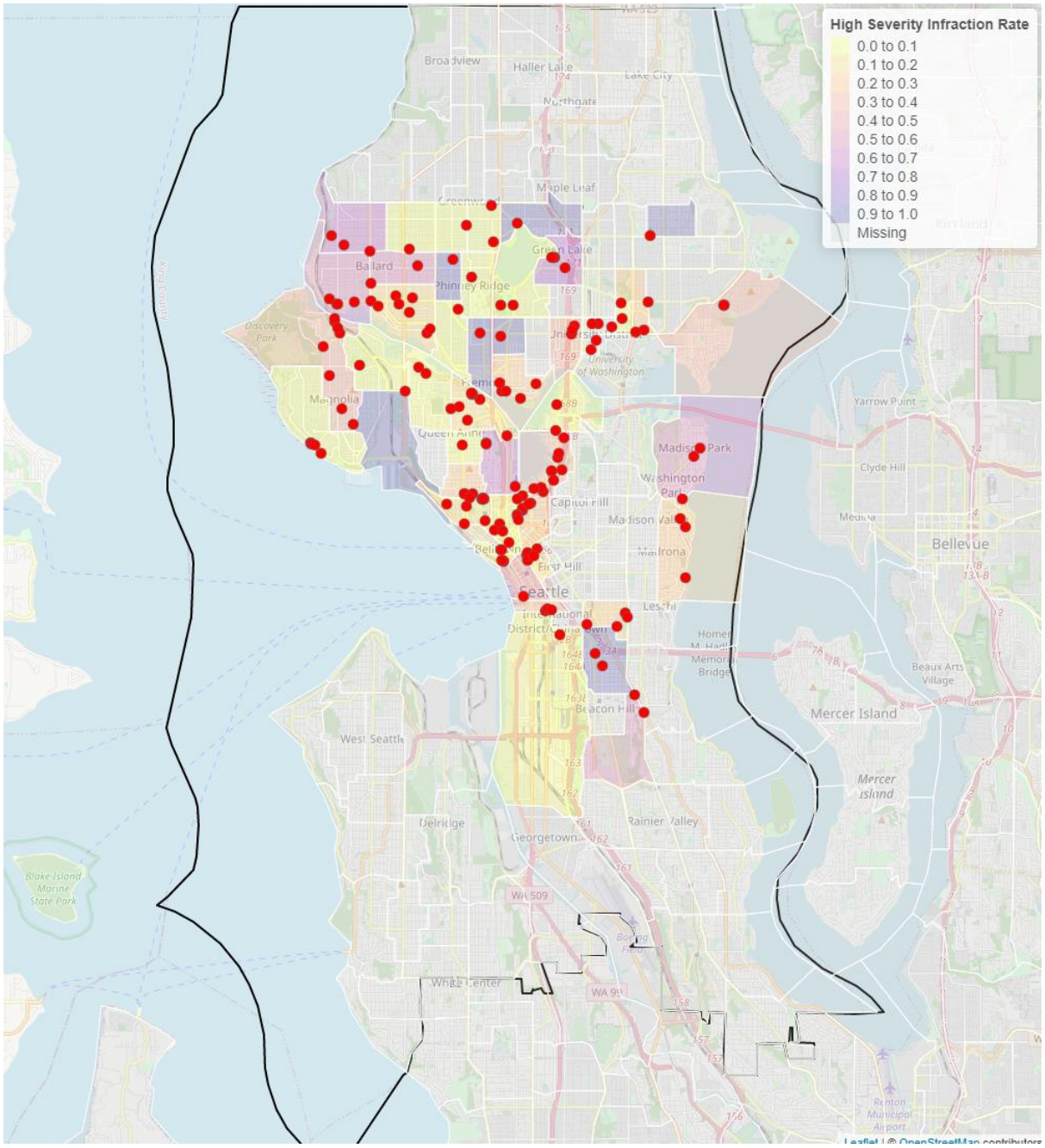

Figure 27: Micromobility high severity parking infraction rates per census tract for the City of Seattle shown with different colors (purple for highest rate bin and yellow for lowest rate bin). High severity means only those with a severity greater than or equal to 7. Interactive version available at: https://rpubs.com/bornakhedri/micromobility-high-severity-parking-infraction-rate

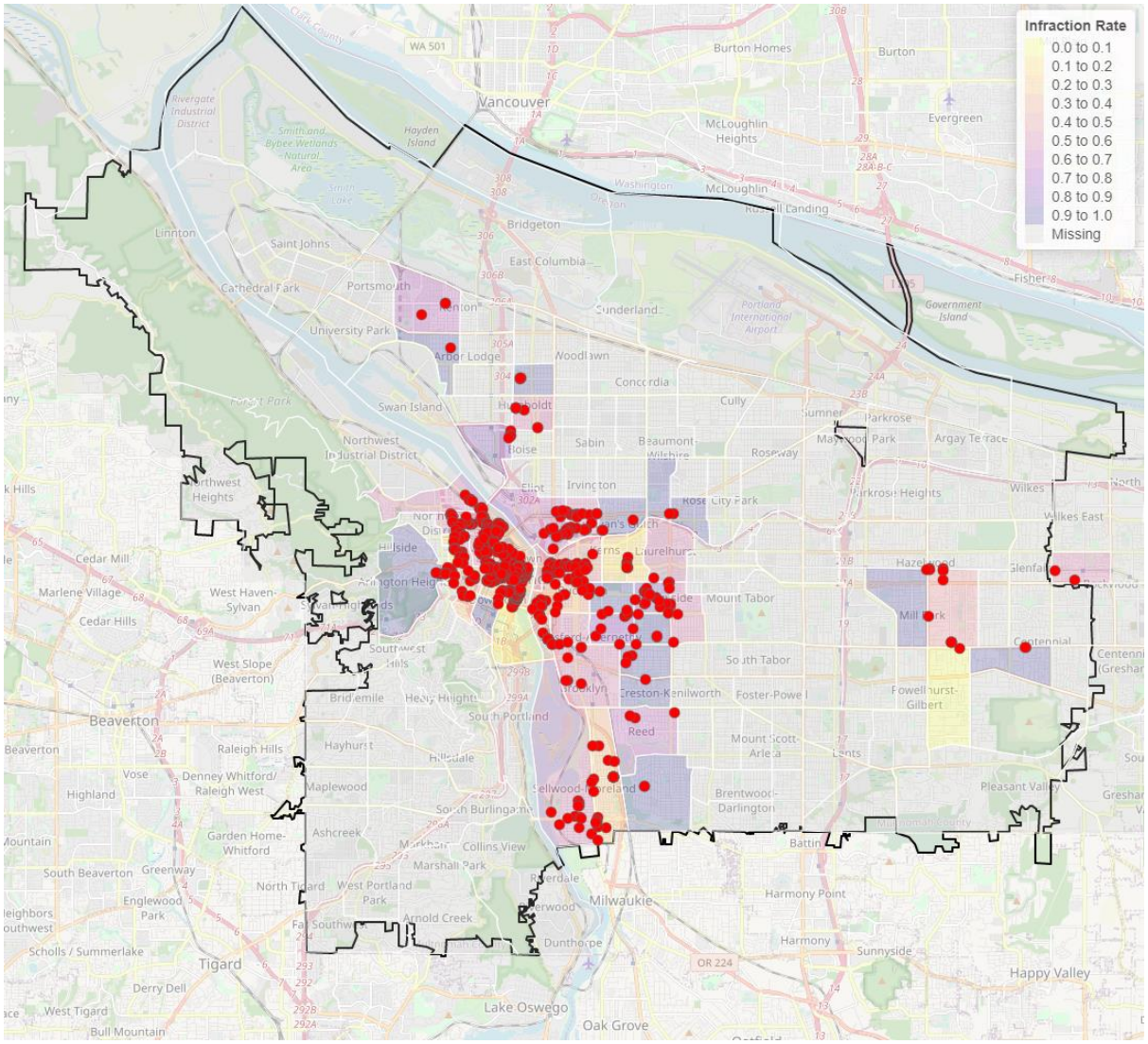

Figure 28: Micromobility parking infraction rates per census tract for the City of Portland shown with different colors (purple for highest rate bin and yellow for lowest rate bin). Interactive version available at: https://rpubs.com/bornakhedri/micromobility-parking-infraction-rate

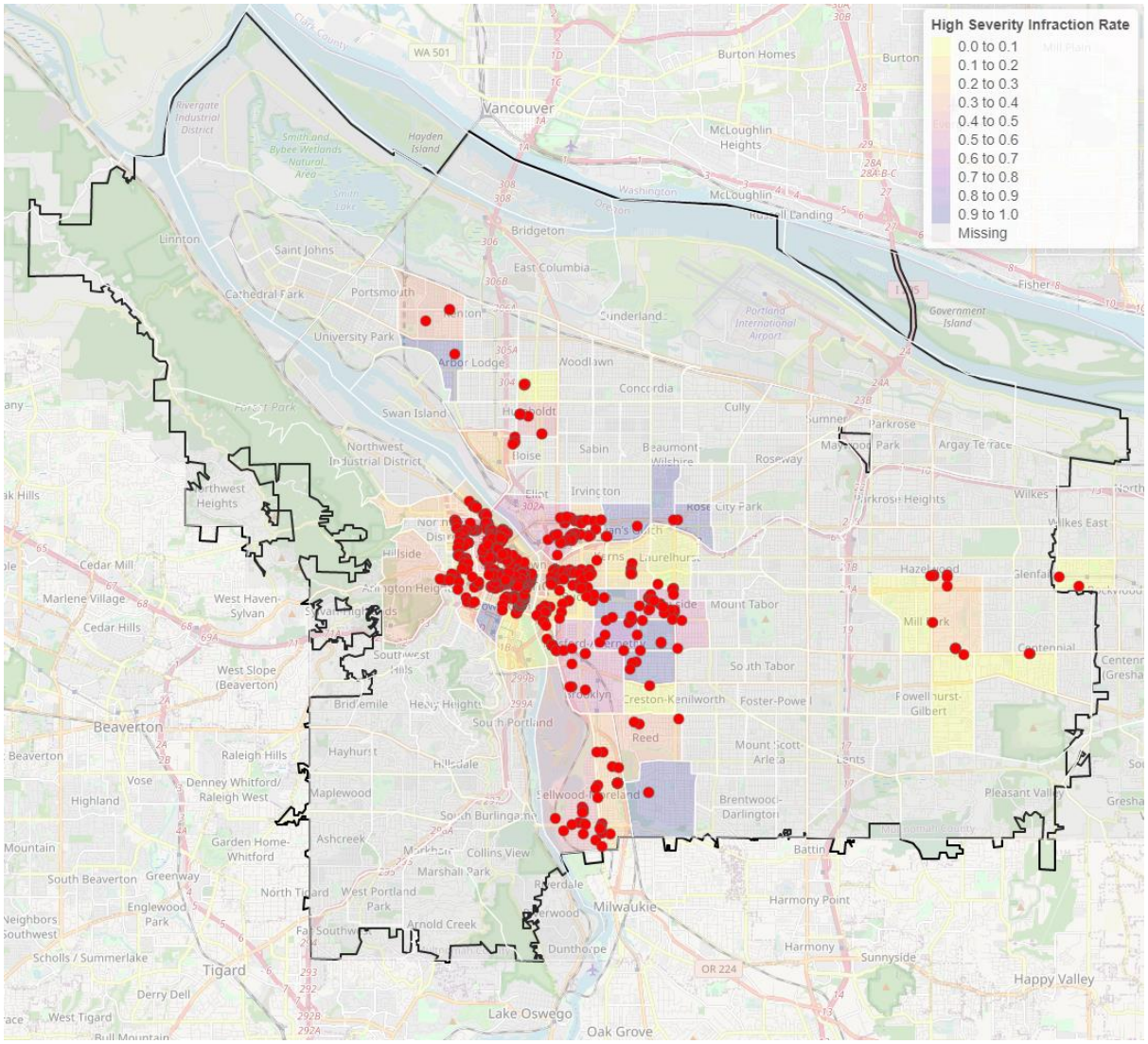

Figure 29: Micromobility high severity parking infraction rates per census tract for the City of Portland shown with different colors (purple for highest rate bin and yellow for lowest rate bin). High severity means only those with a severity greater than or equal to 7. Interactive version available at: https://rpubs.com/bornakhedri/micromobility-high-severity-parking-infraction-rate

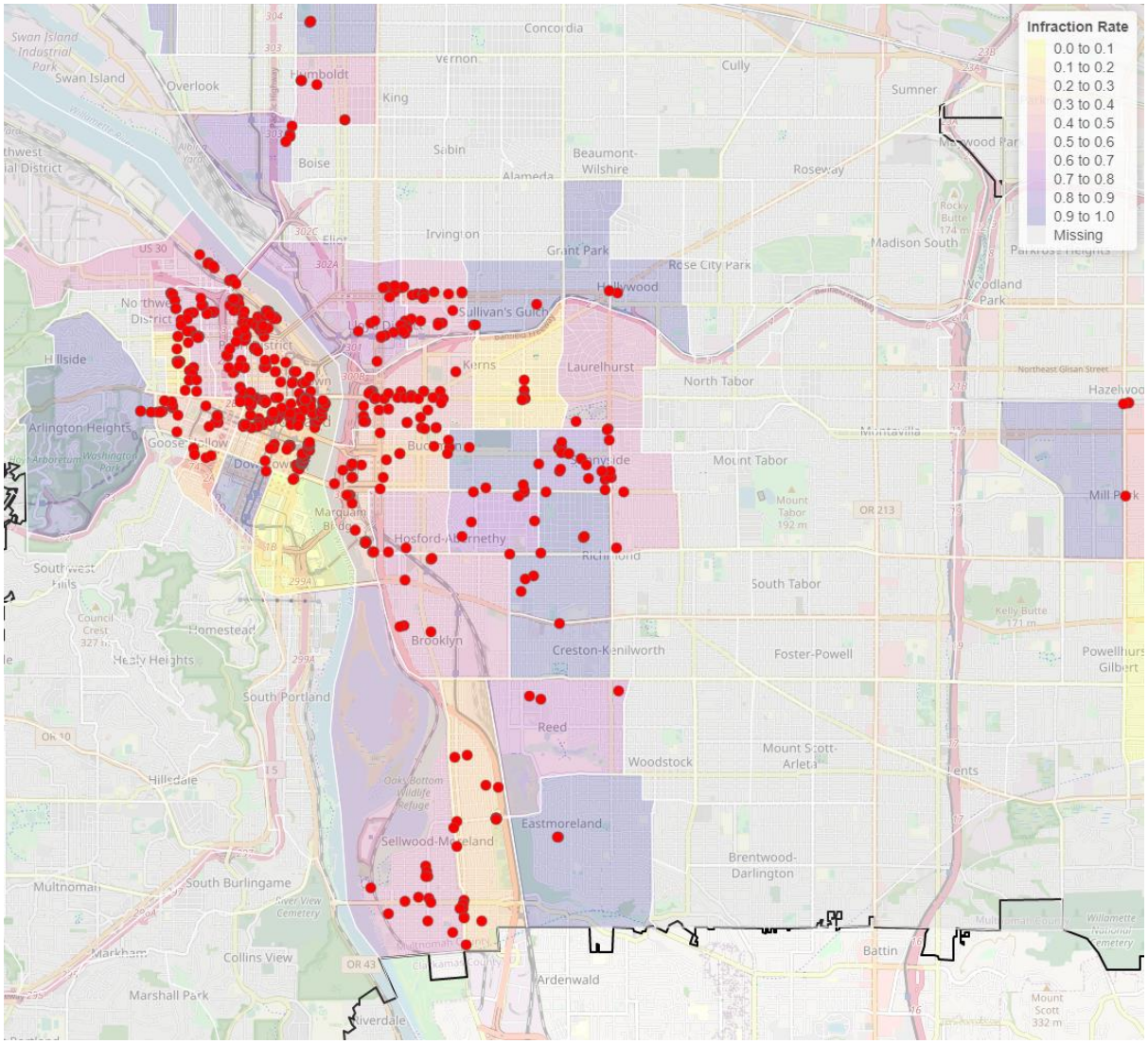

Figure 30: Zoomed in version for Figure 27, concentrating mainly on the Portland central area.

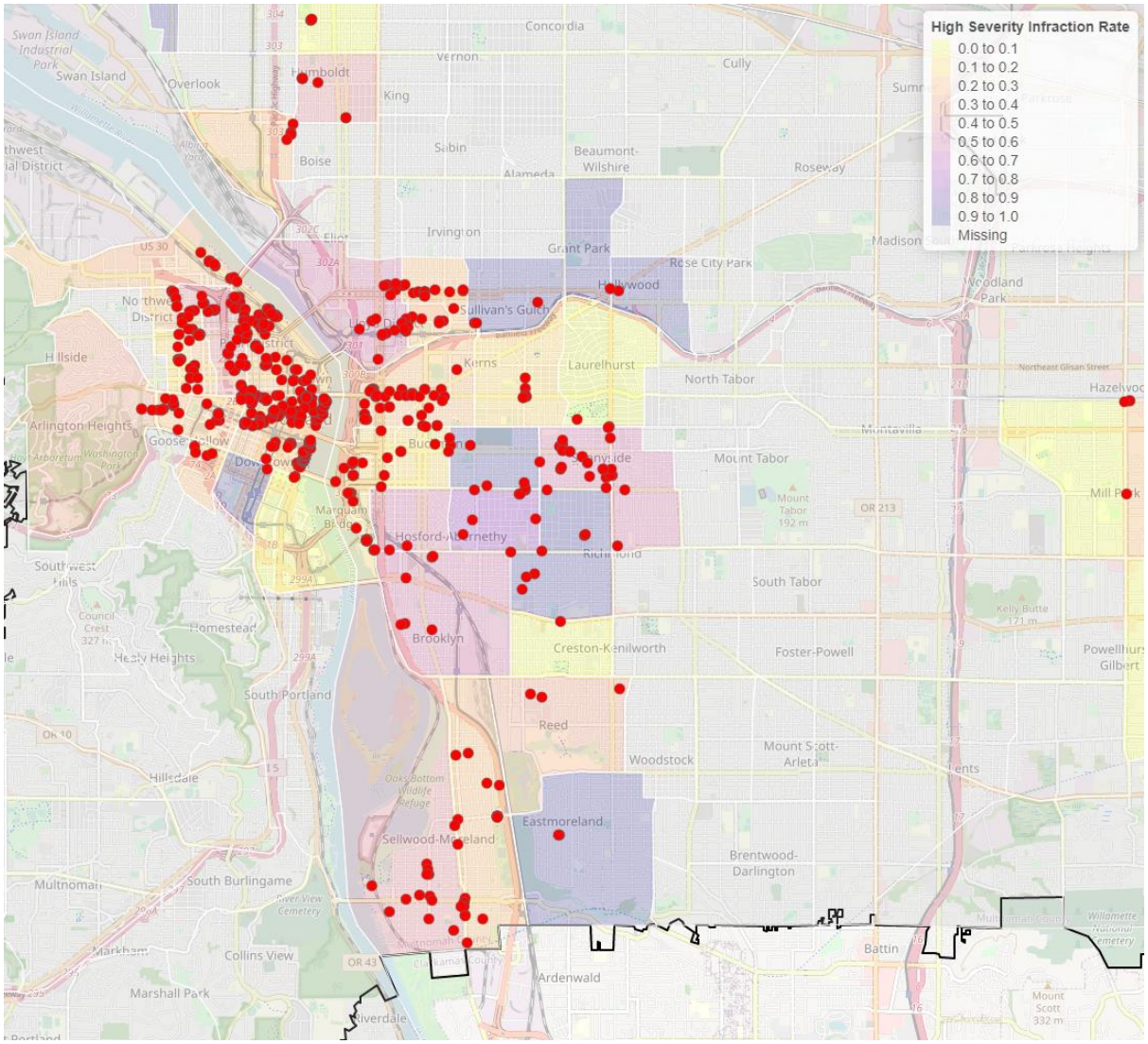

Figure 31: Zoomed in version for Figure 28, concentrating mainly on the Portland central area.

3.8 Data modeling and results

For the data modeling section, census data was gathered through the "tidycensus" package (K. Walker, 2020) in R, from the American Community Survey (ACS) 2019 5-year survey. The variables gathered were: total population, 1st to 5th quartile mean incomes, top 5% mean income, median income, total number of homeowners, total number of vehicles, percentage of white population (to then calculate the minority rate), and median age. These were

gathered for every census tract where at least one report was submitted. Further, the area for each of the census tracts was gathered using the "tigris" package in R (K. E. Walker, 2016). From there on, some other variables were calculated by combining the gathered attributes so far, i.e., percentage of homeowners (number of homeowners / population), minority ratio (1 - white/total population), number of vehicles in a census tract divided by population, and population density (total population / area in squared kilometers).

Data regarding built environment factors were sought as well. Two data attributes that made sense for this analysis were the number of transit stops and the number of bike racks in each census tract. Data for the bus stops in Seattle was collected from King County Metro's GTFS database. Bike racks in Seattle were collected from the City of Seattle's open Geo Data including bike racks owned and maintained by SDOT. Transit stops in Portland were gathered from the TriMet developer resources. Lastly, Portland bike racks were collected from Portland Maps Open Data, although they were not used for the modeling as Portland's micromobility vehicles were all scooters and not bikes.

Eight Ordinary Least Squares (OLS) linear regression models were created from the cleaned data, four for Portland and Seattle each. The final independent variables used were: census tract median age, total population, mean income of the top 5%, median income, portion of home owners, minority rate, average number of vehicles in census tract per person, population density, number of transit stops in each census tract (for both Portland and Seattle), and lastly, number of bike rack in each census tract (for Seattle only). The dependent variable for the four models were: 1) portion of reports in a census tract that were a violation (infraction rate), 2) total number of violations per census tract, 3) portion of reports in a census tract that had a severity of equal to or higher than seven (high severity infraction rate), and 4) total number of reports per census tract. The last dependent variable was particularly

modeled to control for any biases in the data collection and improve understanding of whether the sheer number of reports generated in each census tract was correlated with any of our independent variables.

The main advantage of an OLS model is its simplicity and that it is easy to interpret. However, some of its disadvantages include being sensitive to outliers and that the test statistic might be unreliable if the data is not normally distributed. An alternative would have been the use of a Robust Linear Regression model as there were some outliers in the data. In addition, a logistic regression could also be used to model for each audited vehicle which has a binary label of violation or no violation, which may have kept more richness in the data compared to when it is aggregated over each census tract for a linear regression model.

A stepwise regression method was used to ensure independent variables that have a high correlation with the dependent variable stay in the equation and that insignificant variables are omitted. The model would optimize itself to achieve the highest AIC by going back and forth and dropping or adding independent variables. The downsides of this method are that it is prone to overfitting as well as prone to spurious correlations (i.e., factors that are not causally related and are correlated by coincidence or a third unseen factor). All models start with zero variables, then add the most contributive predictors sequentially, and then remove any variables that no longer provide an improvement in the model. The stepAIC function was used from the MASS package (Venables & Ripley, 2002).

Results for the Seattle model are shown in Table 14. The linear regression model for Seattle showed that the number of transit stops in a census tract is positively correlated with the percentage of violations (violations divided by the total number of reports per each census tract) in that same geography, and the number of bike racks is negatively correlated with the percentage of violations. Per SDOT's policy, which is to encourage users to park their

bikeshare vehicles next to bike racks, we also expected fewer violations in areas with more bike racks. The sheer number of violations in each census tract were also found to be significantly correlated with the same two independent variables in the same manner. The third model showed that percentage of high severity violations negatively correlates with the population density and number of transit stops. The model for Portland, shown in Table 15, did not illustrate as interesting results.

Table 14: Linear regression models for Seattle census tracts

	Infraction Rate		**High Severity Infraction Rate**		**Number of Violations**		**Number of Reports**	
Predictors	*Estimates*	*p*	*Estimates*	*p*	*Estimates*	*p*	*Estimates*	*p*
Intercept	0.684	**<0.001**	0.656	**<0.001**	1.954	**<0.001**	2.330	0.120
Number of Bike Racks	-0.006	**0.020**			-0.032	**0.007**	-0.035	0.064
Number of Transit Stops	0.010	**0.017**	-0.009	**0.025**	0.059	**0.003**	0.066	**0.046**
Population Density (people/sq. km)			-0.00004	**0.043**				
Median Income							0.00007	**0.006**
Portion of Home Owners							-7.342	**<0.001**
R^2 / R^2 adjusted	0.161 / 0.121		0.138 / 0.097		0.225 / 0.188		0.313 / 0.245	
AIC	33.508		34.875		171.266		211.098	

Table 15: Linear regression models for Portland census tracts

	Infraction Rate		**High Severity Infraction Rate**		**Number of Violations**		**Number of Reports**	
Predictors	*Estimates*	*p*	*Estimates*	*p*	*Estimates*	*p*	*Estimates*	*p*
Intercept	1.056	**<0.001**	0.278	0.247	10.015	0.416	63.562	0.113
Population Density (people/sq. km)	-0.00007	**<0.001**	0.00005	0.058	-0.002	**0.006**	-0.005	**0.001**
Portion of Home Owners			0.487	0.067	-20.427	**0.002**	-37.990	**0.027**
Minority Rate			-1.489	**0.031**			-73.252	0.068
Median Age					1.001	**<0.001**	3.480	**<0.001**
Median Income					0.0002	**0.042**		
Number of Cars per Person					-52.836	**0.002**	-200.053	**<0.001**
Number of Transit Stops					-0.150	**0.021**	-0.538	**0.002**
R^2 / R^2 adjusted	0.378 / 0.364		0.221 / 0.162		0.732 / 0.687		0.829 / 0.801	
AIC	18.010		30.684		280.293		362.718	

3.9 Findings and conclusions

This work talked about the development of and the motivation behind a web-based application for the purposes of crowdsourcing micromobility parking infraction data from residents and for conducting data-driven parking audits of micromobility companies. The work benchmarked the way 13 different cities ask citizens to report micromobility parking infractions. It further conducted interviews of five different jurisdictions to ask about key attributes needed for a micromobility parking infraction reporting app. Also, the work studied policies regarding micromobility parking in eight U.S. cities while categorizing them into nine different groups, underlining their similarities and differences. The work presented a sampling plan used for conducting a parking data audit in the cities of Portland and Seattle. Data collected from the two case studies were cleaned and briefly summarized through various plots. Furthermore, the data was analyzed spatially to show the distributions and severities of parking infractions across the two cities. An interactive visualization tool was introduced to count the portion of parking infractions and high severity parking infractions on an aggregate census tract level. Lastly, the data was modeled using an OLS linear regression model to seek relationships between parking infraction and factors of the built environment and socioeconomic and demographic factors.

We found that neighborhoods with more bike racks in Seattle had a less percentage of their reports being parking infractions. Also, areas with more transit stops were found to have a higher percentage of parking infractions. However, these results did not hold true for the data from Portland. It is recommended that the same study be conducted in other cities to find better relationships between the number of parking violations and other built environment characteristics.

One point that this study was aiming to emphasize was the importance of crowdsourced data in performance monitoring of programs in different cities. This app was designed to serve both as an auditing tool for city representatives or contractors, but also for the general public to report parking infractions in their neighborhoods. We also initiated some efforts of coordinating with various cities to deploy this app as a state-of-the-art solution for reporting parking infractions; however, impediments such as the COVID-19 pandemic and the uncertainty for bike and scooter companies during that period, certainly did not help our efforts.

Rooms for improvement and future research could include the use of logistic regression for evaluating whether an infraction would happen or not based on variables such as distance to the nearest transit stop or to the nearest bike rack (instead of looking at numeric independent variable at aggregate level, we can look at individual reports with a dichotomous label of violation or no violation). Furthermore, the use of other state-of-the-art machine learning algorithms for predicting the violation labels based on census tract demographic/socioeconomic factors and/or built environment information could be valuable.

Nevertheless, this tool can be used as a data solution for handling micromobility parking infractions in the long run. The modeling and spatial sections of this study can be used as an analysis framework for cities to evaluate how various micromobility companies are doing and if they are abiding by the rules in their permits.

4 Conclusion

This work was an effort to improve the understanding of effective multimodal transportation design processes and performance-based practical design decision making through conducting a national-scale literature and document review. Chapter 2.2 synthesized the state of the knowledge via reviewing the available academic literature, and Chapter 2.3. synthesized the state of the practice by reviewing practical documents such as design manuals and guidebooks from WSDOT, ODOT, FDOT, MnDOT, and MassDOT, as well as two NCHRP reports. The work introduced key terminology, discussed multimodal performance measures, compared the current design processes across various jurisdictions, and drew conclusions on what jurisdictions should do to advance their multimodal design. The contribution of this work is that it gathers literature from various sources and establishes that both scholarly research and practical guidelines are suggesting relatively similar solutions to advancing multimodal transportation, and that performance-based design and engineering concepts should be adopted by practitioners to ensure access, safety, and mobility for all modes.

The second section of the thesis focused on a new data-gathering tool and analysis framework that could potentially help cities more effectively monitor the performance of micromobility services (i.e., shared e-scooters and e-bikes). The use of a crowdsourcing application developed by our research team could help cities monitor the performance of micromobility vehicle programs. This tool can also be used for conducting data-driven parking audits of bikes and scooters, on a neighborhood and/or a city level. Results from two parking audits in the cities of Portland and Seattle showed that this tool can be used to spatially analyze the data, create summary statistics to compare metrics for various companies, and help spatially analyze the data. Several statistical models were also developed to seek for links between parking violations and elements of the built environment and/or census tract socioeconomic

factors and demographics. This data collection tool and analysis framework can be used by cities to conduct parking audits of micromobility companies, and to ensure that the transportation network and mobility programs are operating successfully through performance monitoring.

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Appendices

Appendix A

Lists of micromobility infraction rules for eight different cities are brought in Tables 16 to 23. The synthesis of all the infraction rules can be seen together in Table 13. The severities were assigned by the researchers of the study. These scores are to some extent subjective based on how much we thought a certain issue had priority. The infraction rules themselves, however, are entirely based on permits studies online.

Table 16: List of micromobility infraction rules for Seattle, WA

Seattle, WA		
No.	Infraction rule	Severity
1	Reducing pedestrian zone clearance under 6 ft.	10
2	A safety/access issue for the disabled	10
3	Blocking access to buildings/structures	9
4	On a moving bridge or rail line/crossing	9
5	In the pedestrian zone of the sidewalk	8
6	In travelways/driveways/bicycle lanes	8
7	In a corner-curb-radius area	8
8	Blocking street features (e.g. benches/crosswalk buttons)	7
9	Blocking access to crosswalks/paths	7
10	Locked to a fixed object (e.g. street sign/fire hydrant)	7
11	In a transit curb zone or within 60 ft. of a transit sign	6
12	In a load/unload or disabled parking zone	6
13	In a geofence-restricted parking zone	4
14	In private property without consent	3
15	In “Seattle Dept. of Parks and Recreation” property	3
16	In “Washington State Ferries” property	3
17	15 or more devices available in a 1000 ft. block face	2
18	On vegetation	2
19	Toppled / Not parked upright	1
20	Otherwise creating a safety hazard	1

Table 17: List of micromobility infraction rules for Portland, OR

Portland, OR		
No.	Infraction rule	Severity
1	Reducing pedestrian zone clearance under 6 ft.	10
2	A safety/access issue for the disabled (e.g. blocking ramp)	10
3	Within 5 ft. of ADA ramp or disabled parking zone	9
4	In a travel, bicycle, or dedicated transit lane	8
5	Within 5 ft. of a driveway, alley, or curb cut	8
6	In the corner of two intersecting sidewalks	8
7	Fastened to street features (e.g. lights/signals)	7
8	Fastened to or placed within 5 ft. of a bicycle rack	7
9	Within 5 ft. of fire hydrant	6
10	In a transit platform	6
11	Within 30 ft. of a bus stop sign, counter to traffic flow	6
12	Within 5 ft. of a loading or taxi zone	6
13	Obstructing access to parked vehicles	5
14	Within 5 ft. of drinking fountain or public art	4
15	In a traffic island, median, or traffic circle	4
16	Within city parks or pedestrian plazas	3
17	In private property	3
18	On a grating, manhole cover, or access lid	2
19	Interfering with utility facilities (e.g. pipes/electrical cables)	2
20	Causing damage to landscaping (e.g. flowers/trees)	2
21	Scooters are in a cluster with more than 10 ft. length	1
22	Two clusters of scooters placed within 20 ft. of each other	1
23	Toppled / Not parked upright	1
24	Otherwise creating a safety hazard	1

Table 18: List of micromobility infraction rules for Redmond, WA

Redmond, WA		
No.	Infraction rule	Severity
1	Reducing pedestrian zone clearance under 6 ft.	10
2	A safety/access issue for the disabled (e.g. blocking ramp)	10
3	In sidewalk café seating areas	8
4	In vehicle lane/bicycle lane/trail	8
5	Blocking access to crosswalks/entryways/paths	7
6	Blocking street features (e.g. benches/fire hydrants)	7
7	In transit curb zone (e.g. blocking bus stop)	6
8	In bike share no-parking area	4
9	In private property without consent	3
10	In one location more than 7 consecutive days	2
11	Toppled / Not parked upright	1
12	Otherwise creating a safety hazard	1

Table 19: List of micromobility infraction rules for Spokane, WA

Spokane, WA		
No.	Infraction rule	Severity
1	In the pedestrian zone with under 6 ft. clearance	10
2	An access issue for the disabled (e.g. blocking ramp)	10
3	Blocking doorways/building entryways	9
4	Blocking driveways/curb ramps	8
5	In a travel lane or off-street	8
6	In the corner curb of sidewalk	8
7	In a block where furniture zone is under 3 ft.	7
8	Blocking street features (e.g. benches & transit info signs) *	7
9	In transit zone (e.g. bus stops & shelters) *	6
10	In load/unload or disabled parking zone	6
11	In private property without consent	3
12	Not parked on hard surface (e.g. planted area)	2
13	In parklets and streateries	2
14	In one location more than 7 consecutive days	2
15	Toppled / Not parked upright	1

Table 20: List of micromobility infraction rules for Boise, ID

Boise, ID		
No.	Infraction rule	Severity
1	Reducing pedestrian travel space to under 6 ft.	10
2	Blocking ADA accommodations (e.g. ramps / signal buttons)	10
3	In entryways and exits (e.g. building evacuation exit)	9
4	On curb ramps or curb cuts	8
5	In a vehicular travel lane or bike lane	8
6	Obstructing pedestrian or vehicular traffic	8
7	On driveways	8
8	On a block without a sidewalk	7
9	Blocking street furniture (e.g. pay stations)	7
10	In transit zones (e.g. bus stops / shelters)	6
11	In loading zones	6
12	In on-street parking spaces	5
13	In geo-fenced parking restricted areas	4
14	Not on hard surface / Placed on vegetation	2
15	In the same location for 24 hours or more	2
16	Toppled / Not parked upright	1

Table 21: List of micromobility infraction rules for San Francisco, CA

San Francisco, CA		
No.	Infraction rule	Severity
1	Reducing pedestrian zone clearance under 6 ft.	10
2	Blocking access points (e.g. doors/ramps/stairs)	9
3	In or along a disabled parking zone (blue curb)	9
4	Blocking access to vehicle or bicycle lanes	8
5	Within 15 ft. of a curb ramp at a corner	8
6	In the corner of two intersecting sidewalks	8
7	Against building facades	8
8	Blocking access to a crosswalk	7
9	In a block face without a furniture zone	7
10	In a sidewalk with less than 9 ft. width	7
11	Next or attached to sidewalk amenities or landscaping	7
12	Obstructing fire hydrants or emergency exits	6
13	Within 15 ft. of a transit zone (e.g. bus stop)	6
14	Within 15 ft. of a loading zone (yellow/white curb)	6
15	Scooter locked to another vehicle on a rack	3
16	More than two scooters parked in an inverted-U-rack	3
17	In one location more than 7 consecutive days	2
18	Toppled / Not parked upright	1

Table 22: List of micromobility infraction rules for Los Angeles, CA

Los Angeles, CA		
No.	Infraction rule	Severity
1	In the pedestrian zone with under 6 ft. clearance	10
2	Blocking ADA access ramps or curb ramps	10
3	In or along a disabled parking zone (blue curb)	9
4	Impeding travel in a driving or bicycle lane	8
5	Within 15 ft. of a curb ramp at a corner	8
6	In the corner of two intersecting sidewalks	8
7	In front of driveways or crosswalks	8
8	In a block where furniture zone is under 3 ft.	7
9	Locked to street furniture (e.g. benches)	7
10	In a transit zone (e.g. bus stops & shelters)	6
11	In or along a red curb zone	6
12	In or along a loading zone (yellow curb)	6
13	In a block face where parking is prohibited by the city	4
14	In private property	3
15	In or adjacent to parklets	3
16	On landscaped areas or grass	2
17	In one location more than 5 consecutive days	2
18	Toppled / Not parked upright	1

Table 23: List of micromobility infraction rules for Washington D.C.

Washington D.C.		
No.	Infraction rule	Severity
1	Reducing pedestrian travel space to under 5 ft.	10
2	Blocking ADA access	10
3	Not within the sidewalk's furniture zone where it exists	8
4	Blocking vehicular travel area (e.g. driving lanes)	8
5	Blocking access to private property entrance or driveway	8
6	Blocking access to Capital Bikeshare stations	7
7	Fastened to fire hydrants and police/fire call boxes	6
8	Blocking access to transit stops and shelters	6
9	Fastened to poles within a bus zone or 25 ft. of an intersection	6
10	Fastened to electric traffic signal poles	5
11	Bike is not locked to legal street infrastructure	4
12	In private property without consent	3
13	Bike/scooter in same location for 5 days	2
14	Toppled / Not parked upright	1