Transportation Transformation: Is Micromobility Making a Macro Impact on Sustainability?

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Abstract

The transportation landscape is ever-evolving in the face of new technologies, including the emergence of micromobility – a new classification given to lightweight human-powered or electric vehicles operated at low speeds. This paper focuses on the role of these new modes in the efforts to cultivate a more sustainable transportation system by reducing GHG emissions, providing a reliable and equitable transportation service, and enhancing the human experience. Existing literature on sustainable transportation systems is used to build a three-goal framework, which is then used to assess the extent to which is micromobility contributes to a sustainable urban transportation system. Next, we identify and discuss policies that can help micromobility achieve better sustainability outcomes. This review of the nascent literature shows that the sustainability impacts of these modes are at present mixed and are likely to remain so without more targeted interventions by local stakeholders. Yet, the operations and use of micromobility systems is quickly evolving and holds promise for contributing to a more sustainable transportation system.

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Introduction

There has been prodigious growth over the past decade of small, on-demand mobility options including shared bicycles (Shaheen et al. 2017) and, more recently, shared, dockless e-scooters and e-bikes (Clewlow 2019; NACTO 2019). These new modes, frequently grouped under the term *micromobility*, have potential to address key aspects of sustainability through three dimensions. First, they may improve environmental sustainability through reductions in private automobile dependence. They also promise to address social and economic disparities in mobility by providing reliable, inexpensive, and equitable transportation that links with transit and other modes. Lastly, the human experience in cities may be enhanced by providing joyful and fun new ways to get around and experience the built environment while reducing barriers to non-automobile travel. These new modes come at a time when many North American cities have seen a resurgence of growth in city centers with a renewed focus on prioritizing walking, rolling, and transit over automobile use. Further, they are positioned to support cities that strive to be smart, connected, and sustainable (Zhou 2012; Broman and Robèrt 2017). Yet, does research support micromobility’s potential and promise to deliver on these three goals of environmental, economic, and social sustainability?

We define micromobility modes as small, lightweight human-powered or electric vehicles operated at low speeds, including docked and dockless e-scooters and bike share systems (SAE International 2019; Dediu 2019). Although conventional, personally-owned bicycles could be categorized as part of micromobility in general, we have elected to focus this review on emerging micromobility modes, such as e-scooters, bike share, e-bike share, and privately owned e-bikes. This is because the sustainability literature associated with these micromobility modes lacks comprehensive treatment due to their novelty and rapid evolution, posing a challenge in understanding the overall ability of micromobility to support sustainable transportation systems. A comprehensive sustainability picture of micromobility is therefore necessary for transportation planners, policymakers, and researchers to guide the targeted use of micromobility to transform transportation systems.

With this in mind, our review of the literature presents a comprehensive overview of the present state and future outlook of micromobility through a sustainability lens. We first synthesize a three-goal sustainable micromobility framework based on a strong foundation of sustainable transportation literature. Drawing on peer-reviewed studies, white papers, and gray literature, we explore the current performance and potential of micromobility modes according to our three-goal sustainability framework. After we assess micromobility according to the framework, we present a suite of planning and policy opportunities to close the gap between micromobility's current and potential sustainability impacts, including future research areas. We close with overall conclusions of our findings and suggestions for future research to fill gaps in the current state of the literature.

Synthesizing a sustainable micromobility framework

There are a multitude of framework types related to sustainability, transportation, and urban systems (see Pei et al. 2010; Zhou 2012 for comprehensive reviews). To the authors' knowledge, no frameworks specific to sustainable micromobility have been previously developed and thus, our first undertaking is to determine what framework(s) to use in evaluating micromobility. We referenced existing literature on sustainable transportation or planning in general. We looked for ways to define sustainable transportation systems and to determine how micromobility should contribute.

Many existing frameworks extrapolate the Brundtland Report's definition of sustainable development—or "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations World Commission on Environment and Development 1987)—to sustainable transportation (Zhou 2012; Pei et al. 2010). Both Zhou (2012) and Pei et al. (2010) note that successful frameworks encompass a holistic view of sustainability centered on a triple-bottom-line that includes environmental, economic, and societal dimensions.

The concept of sustainable transportation has been evolving and maturing since the early 2000s (Zhou 2012). Deakin (2002) describes sustainable transportation as resulting in the emission of fewer greenhouse gases (GHG) and reduction in the use of non-renewable resources (especially petroleum). Sustainable transportation systems can facilitate this through reduced automobile dependence or use (Zhou 2012; Stephenson, Hopkins, and Doering 2015; Banister and Hickman 2013), more efficient vehicle fleets (Kane and Whitehead 2017; Pei et al. 2010), and prioritization of transit, walking, and cycling (Isaksson, Antonson, and Eriksson 2017; Holden, Linnerud, and Banister 2013; Hickman, Hall, and Banister 2013).

Shiller and Kenworthy (2017) add to these dimensions the need to serve multiple economic and environmental goals, increase accessibility, and enhance the livability and human qualities of urban regions. In this context, sustainable transportation systems should reliably connect users to employment and other opportunities while concurrently reducing household transportation costs (Zhou 2012; Kane and Whitehead 2017). Public private partnerships (Canales et al. 2017) and user incentives or discounts (McQueen and MacArthur 2020;

McQueen, MacArthur, and Cherry 2019a; Spin 2020; McNeil et al. 2019) are potential mechanisms through which transportation reliability and affordability can be balanced.

In her definition of sustainable transport, Deakin (2002) also emphasizes the provision of greater equity and access to all, a theme echoed across the sustainable transportation literature. Equity goals related to transportation systems span multiple dimensions of sustainability. They include planning for inclusive, multimodal systems that provide access for all ages and abilities (Arsenio, Martens, and Di Ciommo 2016), conservation of resources to promote intergenerational transportation equity (Holden, Linnerud, and Banister 2013), and systems that fulfill user needs regardless of social, economic, or geographic circumstances (Castillo and Pitfield 2010).

Tumlin (2012) considers even more nuanced aspects that include human nature. In his considerations, sustainability must balance competing objectives, including the triple bottom line of “people, planet, and profit,” or “equity, ecology, and economy” and given the difficulties in this, it must be considered a process, rather than a finite outcome. In addition, he calls for the inclusion of human feelings - inspiration, happiness, belonging, joy, beauty - in this definition, which are much more difficult to measure, but are at the core of human existence.

Drawing on these ideas, we assert that a sustainable transportation system supports mobility and accessibility over the long-term through environmental, economic, and social dimensions. This broad take on sustainability more readily allows for scenario planning and the consideration of trade-offs (Mihyeon Jeon and Amekudzi 2005), making it flexible as applied to rapidly evolving micromobility modes and their impacts.

With this foundation of sustainable transportation literature established, we identified three primary goals that micromobility should achieve in order to be considered a sustainable

(Figure 1). First, micromobility should reduce GHG emissions from the greater passenger transportation system. This can be accomplished by effecting mode shift from automobile travel, avoiding mode shift from transit and walking, and complementing and encouraging new transit ridership. Next, micromobility should operate reliably and equitably through the use of sustainable business models and labor practices while simultaneously implementing equity and affordability programs. Data sharing with municipalities is a necessary piece of this goal in order to provide a means to externally assess progress along these metrics. Lastly, micromobility should enhance the human experience by augmenting the positive utility of travel (Mokhtarian, Salomon, and Redmond 2001), reducing barriers to transportation, and prioritizing rider safety.

Using these goals, we reviewed the most recent literature available on micromobility. We searched Google Scholar, the TRID (Transportation Research Information Database) database, and Web of Science using the following search terms: micromobility, sustainability, e-scooter, e-bike, bike share, case study, active transportation, rebalancing, equity, emissions, safety, and barriers. Given the recent appearance of several micromobility modes and thus a relatively immature body of literature, we relied on a combination of both peer-reviewed and non-peer reviewed literature, the latter including government agency reports, white papers, blog posts, survey results, student theses/dissertations, and press articles. There was an approximately 50:50 split between the reviewed and non-peer reviewed literature. In the next section, we share our findings and evaluate the current performance of micromobility against this sustainable micromobility framework.

[INSERT FIGURE 1]

Assessing the micromobility status-quo

In this section, we discuss the extent to which micromobility is presently contributing to each sustainability goal while simultaneously highlighting its shortcomings. Acknowledging Tumlin's (2012) theory of sustainability as a process, we posit that it is not necessary for micromobility to completely satisfy each goal in order to have a net positive impact on transportation sustainability. Yet, understanding micromobility's current performance toward each goal is necessary to direct future research and to inform policy, both of which will enable micromobility to approach these sustainability ideals.

Goal 1: Reduce GHG emissions

Given that micromobility modes are human-powered or electric light vehicles, micromobility has great potential to reduce GHG emissions by replacing automobile trips due to increases in energy efficiency (Mason, Fulton, and McDonald 2015). Although there is some variation in micromobility trip distances by location and mode, the literature suggests that micromobility appears to be best positioned to replace short automobile trips. This is consistent with earlier findings on the mode-switch potential of cycling (Lindsay, Macmillan, and Woodward 2011; Maibach, Steg, and Anable 2009). A study of e-scooter travel in France found that the majority of trip lengths fell between 1.24 and 1.86 mi (between 2 and 3 km) (6t 2019a). In Washington, D.C., the average e-scooter trip was 0.40 mi (0.65 km), whereas bike share trips for Capital Bike share members were 1.62 mi (2.61 km) on average (McKenzie 2019a). Additionally, given that 48% of automobile trips in the 25 most congested U.S. metro areas are less than three miles (4.83 km) (Reed 2019), micromobility modes have the potential to replace a considerable proportion of automobile trips.

In a Chicago study of the mode shift potential of e-scooters, Smith and Schwieterman (2018a) suggest that automobile trips between 0.5 and 2.0 mi (0.8 and 3.2 km) are in the ideal range for mode switch. This range was determined by evaluating the time-competitiveness of e-scooters compared to automobiles over a series of origin and destination combinations across Chicago. A time-competitive trip was one where a traveler could arrive no more than two minutes later than the time required to drive and park for the same trip during morning peak congestion conditions. Based on this criteria, non-automobile modes would be competitive for up to 75% of automobile trips in the city (compared to 47% of automobile trips without e-scooters).

A recent Uber-funded report estimated potential substitution effects on automobile trips with shared e-bikes in both London and New York City (Clark and Ogunbekun 2018). The authors used regional travel surveys to estimate the number of automobile trips that could have been made by e-bike. These switchable trips were defined as those between 0.6 mi and 9.3 mi (1 km and 15 km) made by travelers between the ages of 16 and 80. Trips where travelers were accompanying children or carrying luggage were excluded from the analysis. While these latter criteria demonstrate potential limitations of micromobility to be accessible for certain groups (children, the elderly, families), results showed that a potential 230,000 vehicle trips in London and 227,000 vehicle trips in New York City could have been taken by e-bike on a given day, saving 484 metric tons of CO_2 emissions per day between the two cities.

Kou et al. (2020) examined walking, public transit, and car trips replaced by station-based conventional bike share in eight U.S. cities. The authors found that the majority of trips replaced by bike share in each city were car trips. They estimated that bike share accounted for reductions in GHG emissions of between 287 g CO_2-eq/passenger-mile saved in Los Angeles and 353 g CO_2-eq/passenger-mile saved in Chicago.

McQueen et al. (2019b) studied the potential impacts of switching a portion of Portland, Oregon’s mode share to private e-bike. Using existing e-bike mileage mode replacement ratios in North America uncovered by MacArthur et al. (2018), they found that by increasing e-bike mode share by PMT to 15%, Portland’s passenger transportation emissions could be reduced by 11%.

As these GHG savings are the direct result of mode substitution, it is useful to understand the mode substitution ratios of trips of various micromobility modes. We summarize the findings of several studies in Figure *2*.

[INSERT FIGURE 2]

Micromobility’s potential to decrease GHG emissions through automobile trip substitution is promising, especially for e-scooters. However, micromobility is also competing with and replacing walking and transit trips, effectively negating some of micromobility’s net GHG emissions reduction benefits. Using Monte Carlo simulations to model a variety of scenarios of e-scooter usage, Hollingsworth et al. (2019) found that e-scooters often exceeded the lifecycle emissions of buses, mainly due to the emissions associated with e-scooter collection, distribution, and short lifetimes.

Yet, when micromobility acts as a complement to transit rather than as a substitute, the potential for micromobility to reduce GHG emissions from transportation is instead augmented. In comparison to walking, micromobility can decrease the time and effort needed to access transit, which in turn expands transit’s reach and increases time competitiveness with automobile trips (Smith and Schwieterman 2018a).

To this end, there is mixed evidence suggesting that travelers actually exhibit micromobility and transit multimodal behavior. Beginning with positive observations, 53% of survey respondents in Austin rated it easy or somewhat easy to access transit via dockless mobility (City of Austin 2018). Surveys across three French cities indicated 15% of respondents made their last trip using an e-scooter and transit (6t 2019a). In San Francisco, 34% of last trips were made to get to or from public transportation (San Francisco Municipal Transportation Agency 2019). In contrast, only 4% of trips in Santa Monica ended at the downtown light rail station, compared to 13% ending at the beach and 28% ending in downtown (City of Santa Monica 2019). Minneapolis found that the majority of survey respondents (57%) combined less than 10% of their e-scooter trips with transit (City of Minneapolis 2019). In Portland, only 12% of respondents said that they used e-scooters to access public transit at least once per week (PBOT 2018a).

The environmental benefits of micromobility-enabled multimodality are therefore elusive in many cities, especially if travelers lack preference for this behavior, as has been demonstrated by McQueen (2020). He modeled e-scooter and transit multimodal mode choice preference using data from a stated choice experiment of 1,900 university students in Portland, OR. The results showed that there was no location in Portland where taking an e-scooter combined with light rail to get to downtown was more preferable than taking a car or bike directly given the current travel time and cost environment. These findings suggest that there is room for improvement in nudging micromobility towards greater use as a first-mile/last-mile solution to transit.

Overall, the mixed results across cities of multimodal behavior also suggests that the propensity for riders to combine e-scooters with transit could be independent of the availability of e-scooters. Perhaps these heterogeneities are based instead on the reliability, frequency, and quality of the transit system, yet this remains to be studied.

Goal 2: Operate reliably and equitably

In order for micromobility systems to act as an equitable and reliable transportation solution in the long-term, they must also be economically sustainable. Increasingly, transportation has become an attractive market for “policy entrepreneurs” (Kingdon 1984) to tackle, particularly with the arrival of technology solutions that decrease the friction of using shared micromobility vehicles. However, balancing the profit motive of private, often multinational companies with the larger service needs of transportation as a localized public good has proved challenging to achieve.

There are few published case studies that illuminate where and how shared micromobility business operations have struggled or succeeded to be economically sustainable. Seattle presents an interesting example, as it has hosted both a publicly-provided bike share system and several privately owned and managed dockless e-bike share systems. Its city government-sponsored system, Pronto, struggled due to its inadequate system scale, station density, geographic coverage area, ease of use, and pricing structure (Peters and MacKenzie 2019). These issues were not necessarily a result of being a station-based system. Instead, several issues were caused by system design and business model decisions. Pronto was eventually decommissioned and replaced by private, dockless e-bike share systems. These systems saw more trips in the first four months than Pronto did in its 2.5 years of operation.

Shared micromobility systems also see particular challenges when it comes to operating in smaller cities, low density areas, and low-income neighborhoods. A study of bike share systems in cities with fewer than 100,000 inhabitants in Switzerland found that low usage rates, high public spending, ignorance of local specificities, low professionalism of staff, and rebalancing issues were potential risks leading to unsuccessful bike share operation (Audikana et al. 2017). Of the Swiss systems, the ones that were well-used had adequate network density, multimodal connections, station placement targeting commuters, local partnerships with businesses and social organizations, resource sharing, and overall communication and transparency with users. However, none of the systems in these small cities were economically self-sustainable as a private venture, and thus relied on public funding for operation. This shows that small cities may not be an attractive venture for private micromobility companies. As a result, there is potential for small cities to be left behind in the proliferation of micromobility solutions. Indeed, many cities have also seen the withdrawal of micromobility services that intend to concentrate resources in cities with better markets, including Atlanta, Phoenix, San Diego, Antonio, Nashville, Dallas, Columbus, Bogota, Lima, and Rio de Janeiro (McFarland 2020; Keenan 2019). These sudden reductions in service came even before the 2020 COVID-19 pandemic.

In addition to ridership and revenue, the economic viability of any company is also impacted by labor costs. Many new micromobility companies have often relied on relatively inexpensive independent contractors to collect, charge, and distribute micromobility vehicles, as explained by McKenzie (2019a). This model was disrupted by a recent California law, AB5, that attempted to regulate “gig economy” labor by better defining who can be classified as an independent contractor. As a result, micromobility companies have suspended hiring independent contractors throughout California, and instead have begun to work with third-party firms that provide staffing. Before the law took effect, a representative from Bird indicated that charging made up 40% of operational costs (Said 2020). Despite this large cost, compensation for chargers was highly variable (Said 2020; McLean 2020), indicating that employment as an e-scooter charger has not been reliable. Additionally, the 2020 COVID-19 pandemic sparked massive tech worker layoffs in the shared micromobility industry (Rose Dickey 2020) or has at least acted as a tipping point for the downsizing of companies that were not already operating sustainably (Wilson 2020). It is not clear if labor costs have made independent economic viability of micromobility firms untenable, however these recent actions suggest that the industry is currently experiencing economic instability. This instability manifests as unreliable coverage, service, and fares.

Micromobility businesses struggle to provide affordability and equity. In a survey of 44 American bike share operators, half cited price or payment system as a barrier for potential users (Howland et al. 2017). Of these operators, 15 cited the cost of running an equity program as a barrier that prevented them from responding to these issues. In addition, others cited lack of bike infrastructure and poor transit connections as challenges in serving certain areas. Lastly, operators of several systems believed that some populations were unlikely to join the system due to negative social status associated with bicycling. Another survey of bike share system stakeholders throughout the U.S. showed that those in small cities were much less likely to be actively working to address equity concerns (McNeil et al. 2019). However, 71% to 79% of surveyed systems did have some kind of equity programs, including ones that target low-income populations, specific geographic areas, racial or ethnic groups, and people of all abilities. Yet, only 61% of these equity efforts included some data collection component. The most-cited barrier to equity programming by bike share systems was lack of funding.

Recently, some cities have required e-scooter companies to address equity concerns as a condition for operation permits. As part of Portland’s first e-scooter trial, e-scooter companies were required to supply a specific number of e-scooters in under-served geographical areas and offer a low-income fare. However, only one company complied with the quota requirement, and only a total of 43 users were enrolled in a low-income plan (PBOT 2018b). Similarly, Santa Monica experienced low e-scooter equity program participation (City of Santa Monica 2019) and has suggested that future equity efforts should include better engagement with the communities that such programs are intended to serve.

During its e-scooter pilot program, San Francisco also incorporated equity requirements when evaluating e-scooter permit requests (Anderson-Hall 2019). Operators approached equity concerns from a variety of perspectives in their proposals, including: 50% off rides for social assistance program beneficiaries, $10 prepaid cards for equity program users that spent $100 in rides once 1,000 e-scooters were in place within the city, two free rides per day, payment with a transit card, prepaid e-scooter cards available for purchase at brick-and-mortar locations, unlocking e-scooters by texting, and a $5 per year pass including unlimited 30 minute rides in a specified service zone. Each company that did receive a permit committed to make at least 20% of their fleet available in city-identified Communities of Concern. Again, actual e-scooter equity program participation was low (San Francisco Municipal Transportation Agency 2019). Specific outcomes of equity initiatives are discussed more in depth in the next section.

In order to continuously evaluate affordability, reliability, equity, and environmental outcomes associated with micromobility, cities need access to micromobilty data describing spatiotemporal supply and demand, user cost, rebalancing operations, user demographics and equity program participation, crashes, and vehicle lifetimes. Because this information is considered proprietary by private firms, cities have encountered issues when entering into data sharing agreements. Portland implemented data sharing requirements as part of its first 120-day e-scooter pilot programing and requested information regarding e-scooter availability, trip origins and destinations, routes, and safety. Yet, companies' compliance with data reporting requirements varied due to lack of universally defined terms and reporting of complaint data did not meet Portland's expectations (PBOT 2018a).

Goal 3: Enhance the human experience

Sustainability frameworks do not often consider the outcome of enhancing the human experience. Yet, we contend that for a mode to be sustainable, it must attract and retain users by adding value to the ways in which travelers experience their daily lives and move through urban spaces. Namely, micromobility should promote transportation equity and access, health and safety, and joy. These factors contribute to habitual mode choice decisions (Schneider 2013). If micromobility modes succeed at being fun, safe, and socially-inclusive, they could effectively shift habitual mode choice.

Electrified micromobility modes including e-bikes, e-bike share, and e-scooters are associated with being enjoyable ways to travel. A French survey revealed 69% of e-scooter users felt it was a pleasant and fun mode (6t 2019a). Among respondents of a North American e-bike survey, a majority (77%) state that they ride their e-bike because it is more fun to ride than a standard bike (MacArthur et al. 2018). In addition, e-bikes attract new audiences through enhancing perceived safety and the joy of riding, and can aid users with physical limitations in cycling (MacArthur et al. 2018; Jones, Harms, and Heinen 2016).

Micromobility modes can also shrink barriers for users. Respondents in France indicated that e-scooters offer time savings and improved flexibility for door-to-door trips (6t 2019a). E-bikes are particularly successful at enabling users to cycle more often and for longer distances than conventional cycle trips (Fyhri and Fearnley 2015). They also allow users to more easily overcome hilly terrain and long distances with less effort (MacArthur et al. 2018). Similarly, users of shared e-bike systems are less sensitive to longer trip distances, reduced air quality, and poor weather conditions compared to conventional bike share users (Campbell et al. 2016).

As the popularity of micromobility modes increases, there is a danger for a reduction in the perceived accessibility of areas intended for pedestrians (ITDP 2015). As one solution, some cities require e-scooter companies to limit the areas where their vehicles are able to operate at full speed, to operate at all, or to be parked using a geofence system (Lime 2020). This has been used to strategically curtail e-scooter usage in open areas, such as parks and promenades, that are highly frequented by pedestrians (Sharp 2019; Thomas 2019). This strategy can facilitate less competition for space in areas that are designed to serve pedestrians.

The media has frequently elevated the potential for dockless micromobility to create hazards for users with disabilities because of improper parking. Along these lines, a Portland focus group found that improperly parked e-scooters impacted perceived access and safety for people with visual impairments and people who use mobility devices (PBOT 2018a). According to the literature, the actual proliferation of improper parking may be overstated, however. An audit of e-scooter parking in San Jose found that only 2% of e-scooters were parked in a way that impacted mobility on the sidewalk (Fang et al. 2018). James et al. (2019) found that only 6% of parked e-scooters blocked the pedestrian right of way in Washington, D.C.. Lastly, Brown et al. (2020) used parking audits across five American cities to find that motor vehicles (24.7%) actually impeded access more frequently than bikes (0.3%) and e-scooters (1.7%).

Across other marginalized and underserved communities, micromobility has been well-received. A survey of 7,000 Americans showed that low-income communities hold a positive view of e-scooters (Populus 2018; Clewlow 2019). Slightly more women than men also held favorable views of e-scooters, showing that e-scooters have the potential to achieve better gender parity than bike share. In Portland specifically, 74% of surveyed Black Portlanders expressed enthusiasm and support for e-scooters (PBOT 2018a). E-scooters were used consistently in a transportation disadvantaged area of town, experiencing over 44,000 trips during the 120-day pilot period. The average trip distance in this location was greater than trip distances in the central city.

In contrast, other e-scooter usage data tells a different story. Santa Monica observed that its e-scooter riders were more often higher-income (47%) and 34 years old or younger (64%) (City of Santa Monica 2019). The majority of respondents were male in e-scooter user surveys in France (66%), Portland (61%), Santa Monica (67%), Minneapolis (60%), and San Francisco (81%) (6t 2019a; PBOT 2018a; City of Santa Monica 2019; City of Minneapolis 2019; San Francisco Municipal Transportation Agency 2019). There is clearly a disparity in who holds a positive perception of e-scooters and who actually uses them.

Bike share has also seen positive views among low-income communities of color in Chicago, Philadelphia, and New York (McNeil et al. 2018). When comparing bike share users with private cyclists in Washington, D.C., bike share users were more likely to be female and younger, to have lower household incomes, and to own fewer cars and fewer bicycles and were more likely to cycle for utilitarian purposes. (Buck et al. 2013). Even so, findings from 2018 show that CaBi users in Washington, D.C. still tended to be more male (58%) than female (42%) (Virginia Tech 2018).

There are mixed results with respect to availability as a major barrier to micromobility usage, despite its direct impacts on the operations of micromobility companies. Among French survey respondents, 24% state that they often give up renting an e-scooter because none are available nearby (6t 2019a). Yet, in the Austin survey, higher availability rated lowest as a perceived solution to making someone more likely to take dockless mobility (City of Austin 2018). McQueen (2020) found that, all else held at average, decreasing the time required to access an e-scooter for a combined e-scooter and light rail trip to downtown Portland still did not make it more preferable than bike or automobile modes. A follow-up equity analysis of Seattle's second micromobility iteration, involving dockless e-bike share systems, found that neighborhoods with higher per capita bike availability also had more college-educated residents, local community resources, and higher incomes (Mooney et al. 2019). Rebalancing destinations were strongly correlated with neighborhood demand (calculated by taking the inverse of "idle time"). In general, these inequities were described as modest, and the authors did not observe any significant access disparities between neighborhoods of differing racial/ethnic composition or gentrification-related housing displacement risk. It is curious that these economic inequities did not correspond with racial inequities, although it is possible that the aggregation of neighborhood characteristics could have obscured racial inequities that may have appeared had individual user characteristics been used.

Compared to the availability of micromobility modes, the research more clearly identifies cost and accessibility barriers disproportionately impact low-income communities and communities of color, as revealed by a national study of bike share systems (McNeil et al. 2019). Some solutions to these barriers that have been used include equitable cost and discount structuring and unbanked-friendly payment methods (Howland et al. 2017). Systemic and individual racism may also prevent these users from using micromobility more frequently. Despite their stated enthusiasm for e-scooters in Portland (PBOT 2018a), Black Portlanders expressed concern for the potential to be the target of racial profiling and harassment while using e-scooters (PBOT 2018a). Braun et al. (2019) also found that areas with lower education levels, lower socioeconomic status, and higher Hispanic population had significantly less access to bike lanes. Thus, any broader efforts to address the disadvantages and oppression of people of color and other marginalized groups can only improve the transportation outcomes of micromobility.

New safety risks introduced by micromobility may limit the extent to which micromobility enhances the human experience, as such risks would mitigate feelings of joy associated with micromobility modes. Several studies and surveys revealed that bike share and e-scooter users do not tend to wear a helmet (Buck et al. 2013; 6t 2019a; Austin Public Health 2019; Trivedi et al. 2019). In France, the feeling of not being safe was the second top drawback to riding an e-scooter cited after the price (6t 2019a). In Austin, TX, a third of interviewees injured in an e-scooter crash were injured on their first ride (Austin Public Health 2019). E-scooter users have experienced fractures, head injuries, contusions, sprains, and lacerations (Trivedi et al. 2019).

Similar to issues surrounding parking, it is possible that the media has over emphasized aggregate safety risks of micromobility. Portland recorded a total of 176 emergency room visits in Multnomah County due to an e-scooter during the first e-scooter trial, or about 0.025% of e-scooter trips (PBOT 2018a). This total number of visits was actually lower than bicycle visits during the same period, however the total number of bicycle trips in the region is unknown. A North American survey of e-bike riders found that 80% of e-bike riders have never experienced a crash. Of those that did have a crash, only 19% believed that their e-bike contributed in a significant way. More than half of the reported collisions resulted in no injury or mild injuries (MacArthur et al. 2018).

Policy solutions that promote sustainable micromobility outcomes

While we have found that micromobility is already successfully contributing to a sustainable transportation system through some aspects of our tri-faceted framework, we also found several shortcomings. We focus this section on summarizing several policy and planning actions to help micromobility address these areas for improvement. While by no means comprehensive, our suggestions provide near-term actions that can enhance the sustainability outcomes for micromobility modes.

The Built Environment as a support for multimodality and accessibility

Design guides specific to micromobility, like the design guides published by the National Association of City Transportation Officials (NACTO n.d.), would be useful to guide urban policy around future streetscape development in order to enhance micromobility uptake and effective mode shift. These may provide guidelines for micromobility that clearly define operating spaces. Transitions from conventional bike to multimodal micromobility lanes may help this effort, as well as improve overall system safety by separating pedestrian and vehicle travel. Guides may also offer suggestions for signage to improve wayfinding to popular destinations, routes, or parking. Municipalities should integrate shared mobility planning with new street designs, accounting for shared mobility in traffic safety initiatives such as Vision Zero (ITDP 2015).

Parking locations that are strategically placed can connect users to transit systems in order to facilitate multimodal trips. Governments should guide and regulate micromobility companies to complement transit, not compete with it. Incentives might be used to provide service to under-served areas, extend the reach of transit, and increase transportation access (ITDP 2015); however, the efficacy of these incentive programs remains to be tested. This could take the form of a discount to the cost of a micromobility trip when combined with transit. Additionally, integrated payment systems and discounted combination fares could simplify multimodal trips involving a micromobility mode and transit.

Careful consideration should be used when deciding whether a micromobility system should be docked or dockless. Dockless systems can introduce a level of user autonomy that results in increased ease of use (parking at destination) and usage friction (inability to find vehicles when needed). In addition, the challenge of charging and rebalancing is greatly complicated in a dockless system, whereas a docked system possesses less geographic variation in vehicle distribution. Systems of electrified vehicles especially could benefit from being a part of a docked system, in that the charging infrastructure can be integrated into the dock, negating the need for staff members or contractors to gather vehicles for the sole purpose of charging.

While these short-term actions that directly impact micromobility operations are important, long-term and broader shifts in land use and development patterns are necessary to make micromobility, walking, and transit increasingly competitive modes against private automobiles. Improved walkability (Johansson et al., 2016; Leslie et al., 2005) and densification of land use are important for reducing travel distances to employment and other amenities, bringing these trips within an acceptable range for micromobility use. Banister (2011) calls for planning practices to reduce the distances between people and their required destinations through mixed-land use and multimodal transportation networks. Such development could allow for micromobility, in combination with transit, to be used for most trips, reducing the need for automobile travel.

Increased Use of Data: Sharing Agreements, Standards, and Analysis

One obstacle to achieving more sustainable and equitable operations and unbiased evaluation of micromobility is the lack of information with which to plan, design and regulate these modes. Obtaining access to the data is the first hurdle. Service providers are often reluctant to provide proprietary trip-level information. However, the data describing frequent origins/destinations, routes, time of day, and basic user characteristics are important for planners. Information about vehicle rebalancing and charging operations, durability, and lifecycle assessment is necessary for establishing industry-wide regulations. Even more challenging are reporting of vehicle usage ordinance violations and crashes. Cities can work together, through organizations such as National Association of City and Transportation Officials (NACTO) to leverage their collective power to negotiate standardized data sharing, fair use, and privacy agreements with firms as a condition for operating permits (Dupuis et al. 2019). Cities could take a more active approach in obtaining and sharing this data in order to better inform their own equitable planning processes. Chicago has acted as a trailblazer in this regard, as it currently offers comprehensive data from rideshare companies online (Chicago 2020). If more cities followed suit, the operations of micromobility companies would become more transparent.

There are some established efforts to standardize data for operations and demand. Examples include the Mobility Data Specification (MDS) (Open Mobility Foundation [2018] 2020), first developed for use by the Los Angeles Department of Transportation, and the General Bike share Feed Specification (GBFS) (North American Bikeshare Association n.d.). MDS provides historical micromobilty data, such as the number and distribution of operating vehicles at some point in time. In contrast, GBFS provides real-time bike share system data. Both systems are models for data standardization that provide a platform for evaluation that would better enable cities to measure the extent to which micromobility is in alignment with sustainability goals. But questions remain concerning how and where data are archived and stored, company pushback regarding the disclosure of proprietary information, and the general heterogeneity of the landscape of regulations, data formats, and firms.

Even with standardized data sharing platforms, many municipalities may lack the capacity to fully exploit these data. To facilitate data management and analysis, cities may need to enhance their data science staff or partner with universities or third parties. Public agencies may also have concerns about protecting user privacy with requests for public records under the Freedom of Information Act (FOIA). Contracts with third party data managers, such as Ride Report (Ride Report n.d.) and Populus, might help alleviate this issue. Universities and consulting firms can aid cities with the processing and analysis of these "big data" in the short term and ensure that future transportation workforce will have data science skills in the long run (French et al. 2017). For example, faculty at Portland State University were engaged to assist in the analysis of Portland's e-scooter pilot programs (Dill 2019). Additionally, the Federal Transit Administration has offered grants for projects that explore the integration of transit with new mobility options in integrated smartphone apps through the Mobility on Demand (MOD) Sandbox Program (Federal Transit Administration 2020).

Adopting an Equity and Mobility Justice Lens

Equity issues abound in the planning, design, operation, and finance of transportation infrastructure and services (DiCiommo and Shiftan 2017), including micromobility. Addressing the equity concerns of our sustainability framework will take significant and constant effort. To remedy this, cities will need to take an equity and justice lens in all aspects of transportation, including micromobility (Martens 2016; Pereira et al 2016; Sheller 2018; Sheller 2019).

McNeil et al. (2019) enumerate several disparities in micromobility systems including the provision of stations and vehicles, service area boundaries, rebalancing efforts, income-based discounts, payment structures, cash pay option, reduction of fees, facilitated enrollment, encouragement and education programs, prescribe-a-bike, organized rides, outreach and marketing campaigns, non-English offerings, adaptive bicycles, electric bicycles, hiring practices, employee training, and transit integration (McNeil et al. 2019). As illustrated in Portland, cities may need to require the placement of micromobility vehicles in certain areas in order to ensure equitable spatial access to the system (PBOT n.d.; ITDP 2015). At the same time, care must be taken to avoid the creation of service islands if a company decides to reduce service (Bailey, Jr. 2019). Further, seasonal variation in service should not hinder the reliability of micromobility year-round for those vulnerable populations with already limited transportation options.

Awareness and availability of a mode is key in habit building patterns (Schneider 2013). These strategies, however, are not as effective if micromobility supportive infrastructure, such as bike lanes, are not already available in communities of concern. This lack of available facilities has been proven to more often exist in areas with residents of lower education and lower socioeconomic status, as well as areas with higher Hispanic populations (Braun et al. 2019).

There are additional equity complications in using trip-level data to inform decisions about micromobility services (Nguyen and Boundy 2017). Barriers may inhibit the needs of several groups, such as low-income communities, communities of color, people with disabilities, and underserved neighborhoods, from being reflected in these data sets. The same systemic barriers that prevent micromobility use also hamper their appearance of these communities in other passively collected travel data, such as smartphone, smart card, and credit card transaction data. Golub et al. (2019) found that although a higher proportion of people of color had a smartphone (91%) compared to non-Hispanic white respondents (89%), 64% of people of color had access to a credit card or prepaid card account (compared to 79% of non-Hispanic white respondents), and 84% had a checking or savings account (compared to 95% non-Hispanic white respondents). People or color were also less comfortable linking their bank account or credit card to transportation apps on their phone than non-Hispanic white respondents. As such, there are equity implications when basing policy decisions strictly from the use patterns of current users and overlooking those who are not represented by the data.

One of the catalysts needed to address equity issues as well as sustainable business operations is the partnerships between local governments and service providers. These partnerships are key to establishing and implementing policies, funding, and regulations to meet equity and larger sustainability goals. During the permitting process, governments should welcome providers that can deploy reliably at scale. System size, density, spatial coverage, and long-term dependability are important in achieving critical demand and access for all. Additionally, government subsidies for micromobility operations can help guide operations in the direction of transportation planning and sustainability goals. “Stick” policies, such as fleet size reduction and permit revocation could also be used in concert with subsidies to encourage adherence to regulations.

Micromobility companies benefit from public infrastructure such as bike lanes, curb space and so should be held responsible to help fund their maintenance (ITDP 2015) through tools such as permitting fees and per-ride fees. It should be noted that there is a potential for these fees to be passed directly to user in the form of pay-to-unlock fees. There should be regulatory framework in place to address what portion of fees are allowed to be attributed to users versus the operator itself, especially where equity concerns may arise.

Boosting Behavioral Change in Transportation

The first goal in our sustainable transportation framework hinges on shifting travel away from automobile use and towards multimodality. Thus, policies and programs that prompt and maintain these mode shifts are needed. Successful transportation demand management programs will likely involve carrots and sticks to discourage trips by automobile and encourage travel by sustainable modes. We focus here on those policies aimed specifically towards micromobility and not those targeted towards other modes, such as pricing policies and transit incentives, acknowledging, however, that these are an important part of a comprehensive strategy.

Cities can actively target neighborhoods with disproportionate shares of short auto trips (Reed 2019) for micromobility interventions in order to have a better chance of effecting mode shift. As Yang (2010) suggested that limiting fossil-fuel alternatives could be an effective policy tool in promoting the use of electric vehicles, such measures are also necessary in promoting micromobility use as a more sustainable option. It will take courageous policy to fashion micromobility trips in combination with transit as a more practical and utilitarian transportation choice than using private or shared vehicles. As such, micromobility offerings should exist symbiotically with policies that aim to deter automobile use, including parking management and congestion pricing (Hamre and Buehler 2014; Shoup 2017; Green, Heywood, and Navarro 2016; Meng, Liu, and Wang 2012).

Policies geared towards enhancing the human experience should emphasize the positive utility of travel—the idea that travel is not just a derived demand, but has its own intrinsic value—potential of micromobility to encourage use (Mokhtarian, Salomon, and Redmond 2001).

Drawing on the connection between Maslow’s hierarchy of needs and sustainable transportation systems outlined by Tumlin (2012), micromobility should involve human agency in order to effectively impact sustainability, as this is necessary for humans to connect their actions now to future consequences.

Cities or companies can use gamification to encourage certain behaviors. Use of micromobility can be presented as a fun activity using smartphone apps that connect use to games, competitions between friends, or rewards systems (e.g., reduced transit fare for a multimodal trip or proper parking of scooters). This is a critical strategy for municipalities to take moving forward, if micromobility is to be truly integrated into the transportation system as a sustainable asset.

Conclusions and Future Research

In this review, we have used existing literature to develop a three-goal sustainability framework for micromobility that assesses the degree to which they: a) achieve GHG reductions and mode shifts away from automobiles; b) operate reliably and equitably through sustainable business and labor practices and the establishment of equity and affordability programs; and c) enhance the human experience by augmenting the positive utility of travel, reducing existing transportation barriers, and by prioritizing safety. In most of these dimensions, micromobility is falling short of achieving these goals. However, they have enough promise to be considered as potentially important components of a sustainable transportation system in the future.

It is a positive sign that many micromobility modes are replacing automobile trips in several cities (Buck et al. 2013; Campbell et al. 2016; Virginia Tech 2018; Fishman, Washington, and Haworth 2015; Fuller et al. 2013; Zhu et al. 2013; 6t 2019b; City of Santa Monica 2019; City of Minneapolis 2019; San Francisco Municipal Transportation Agency 2019;

PBOT 2018a). Yet, the high percentage of walking trips and notable percentage of transit trips replaced by all micromobility modes is counterproductive given the public resources committed to transit, and calls in to question the net-negative GHG emissions of micromobility (Hollingsworth, Copeland, and Johnson 2019). There may be important reasons why transit riders are switching to micromobility modes for some trips and more investigation is needed to understand and consider these factors in policy and operations. It is also unclear if the GHG reduction impacts of micromobility are significant when viewed at a system-wide scale (McQueen, MacArthur, and Cherry 2019b), rather than from a more narrow assessment.

One way that cities could reduce overall automotive mode share and GHG emissions is by encouraging multimodal micromobility and transit trips to replace longer car trips (Smith and Schwieterman 2018b). Currently, there are mixed findings when it comes to actually observing this multimodal behavior among e-scooter users (6t 2019b; San Francisco Municipal Transportation Agency 2019; City of Santa Monica 2019; City of Minneapolis 2019; PBOT 2018a; McQueen 2020). Multimodality appears to occur more frequently in cities with transit systems that offer a high level of service. This could mean that the quality of transit is a more impactful driver of multimodality than micromobility itself, an argument that requires further study but supports increased transit investment. However, coordination in planning and operations of all of these modes is critical if they are to be complementary and make the most of the public investment in them.

Micromobility systems must be reliable and equitable in order to foster sustainability. The ability of micromobility companies to fulfill this goal hinges on a stable business model, fair labor practices, and impactful equity programs. Although few academic studies have approached these topics, micromobility companies have recently experienced a great deal of instability, manifested both in staying power in specific markets (McFarland 2020; Keenan 2019) and questionable labor practices (McKenzie 2019b; Said 2020; McLean 2020; Rose Dickey 2020; Wilson 2020). Operators blame budget constraints in hampering their ability to achieve equity goals (Howland et al. 2017; McNeil et al. 2019). Transparent and uniform data sharing is necessary to understand the long-term economic success of micromobility companies and to ensure the effectiveness of equity programs. These are critical ingredients for providing a reliable, practical, and inclusive transportation solution.

Finally, enhancing the human experience is critical because it influences habitual mode choice (Schneider 2013) and thus necessary to realize any substantial mode shift away from driving. In its current forms, micromobility has seen some success on this front. Electrified micromobility is often perceived as an especially enjoyable way to travel (6t 2019b; MacArthur et al. 2018; Jones, Harms, and Heinen 2016). Conversely, focus groups (PBOT 2018a) and the media have suggested that micromobility, specifically dockless micromobility, have negatively impacted the other users through improper parking and safety issues. However, some research suggests that these issues are not widespread (Fang et al. 2018; James et al. 2019; Brown et al. 2020; MacArthur et al. 2018; PBOT 2018a).

Along the lines of equity and improving the human experience for all, e-scooters in particular have been perceived positively among a diverse range of socioeconomic groups, including low-income communities, women (Populus 2018; Clewlow 2019), and African Americans (PBOT 2018a). Bike share has also shown positive perception among low-income communities of color (McNeil et al. 2018). Yet, diverse travelers may not actually be embracing micromobility, as usage data tells a different story (City of Santa Monica 2019; 6t 2019b; PBOT 2018a; City of Minneapolis 2019; San Francisco Municipal Transportation Agency 2019;

Virginia Tech 2018; Buck et al. 2013). Cost and payment barriers (McNeil et al. 2019; Howland et al. 2017), systemic and localized racism (PBOT 2018a), and spatial heterogeneities in micromobility-supportive infrastructure availability (Braun, Rodriguez, and Gordon-Larsen 2019) could all be contributing to this phenomenon. In order to better understand the reasons for this gap between perception and ridership of diverse groups, future research should consider that the needs of underserved communities may not come across if they are underrepresented. Cities need to understand how to better support these groups if they hope to enable micromobility to thrive in the long-term.

Micromobility research is needed to inform sustainability in numerous areas, including latent demand, localized mode shift, safety and public health, and mode shift equity impacts. Research can assist policy and planning by defining the contexts where micromobility is competitive with motorized modes and developing tools to increase time and fare competitiveness for desired mode shares. Research exploring what carrot and stick regulatory enforcement actions are effective tools in achieving desired behavioral outcomes has been long overdue. For example, identifying mechanisms that facilitate targeted mode shift and mode retention, perhaps through integrated fares or discounts, is needed. The ability for bicycling infrastructure to be modified to serve a wide range of micromobility vehicles is critical. More is required to understand the performance of micromobility as it relates to the reduction of GHG emissions, including life cycle analyses and the impacts of increased multimodal micromobility and transit trips.

With targeted public oversight, inter-organizational cooperation, and guidance, micromobility could become an integral part of a more sustainable transportation system. Micromobility may greatly reduce urban auto-dependency if it evolves symbiotically with transit, cycling, and walking and considers the wide-ranging needs and capabilities of a heterogeneous population. To this end, the planning practice should continue to support pedestrian-oriented environments and shorter distances between destinations. Investment in public transit should not be overlooked, as transit provides the backbone necessary for an increase in multimodal micromobility trips. Although micromobility has not yet fully achieved its sustainability potential, the fact that it can arrive, iterate, and adapt quickly is a promising sign that it can be harnessed for success.

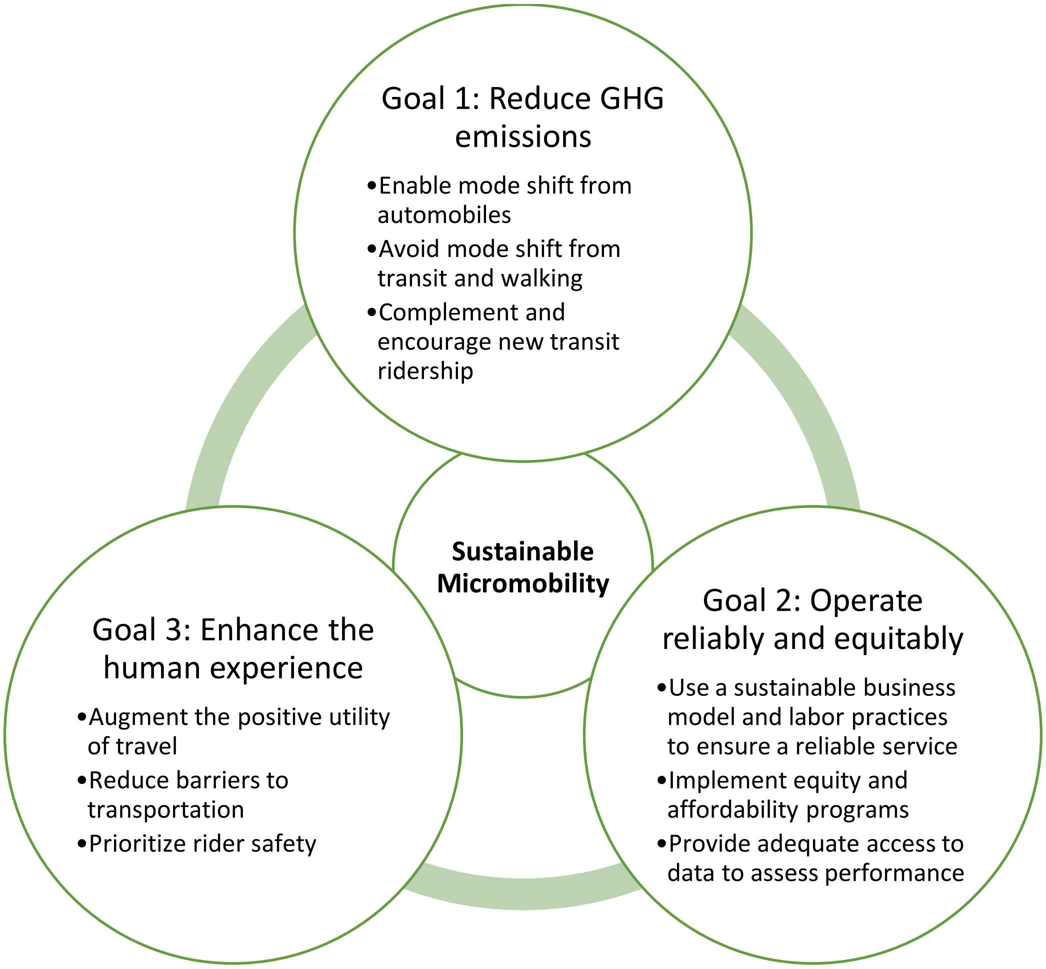

Figure 1 Sustainable Micromobility *Framework:* Goals and Mechanisms

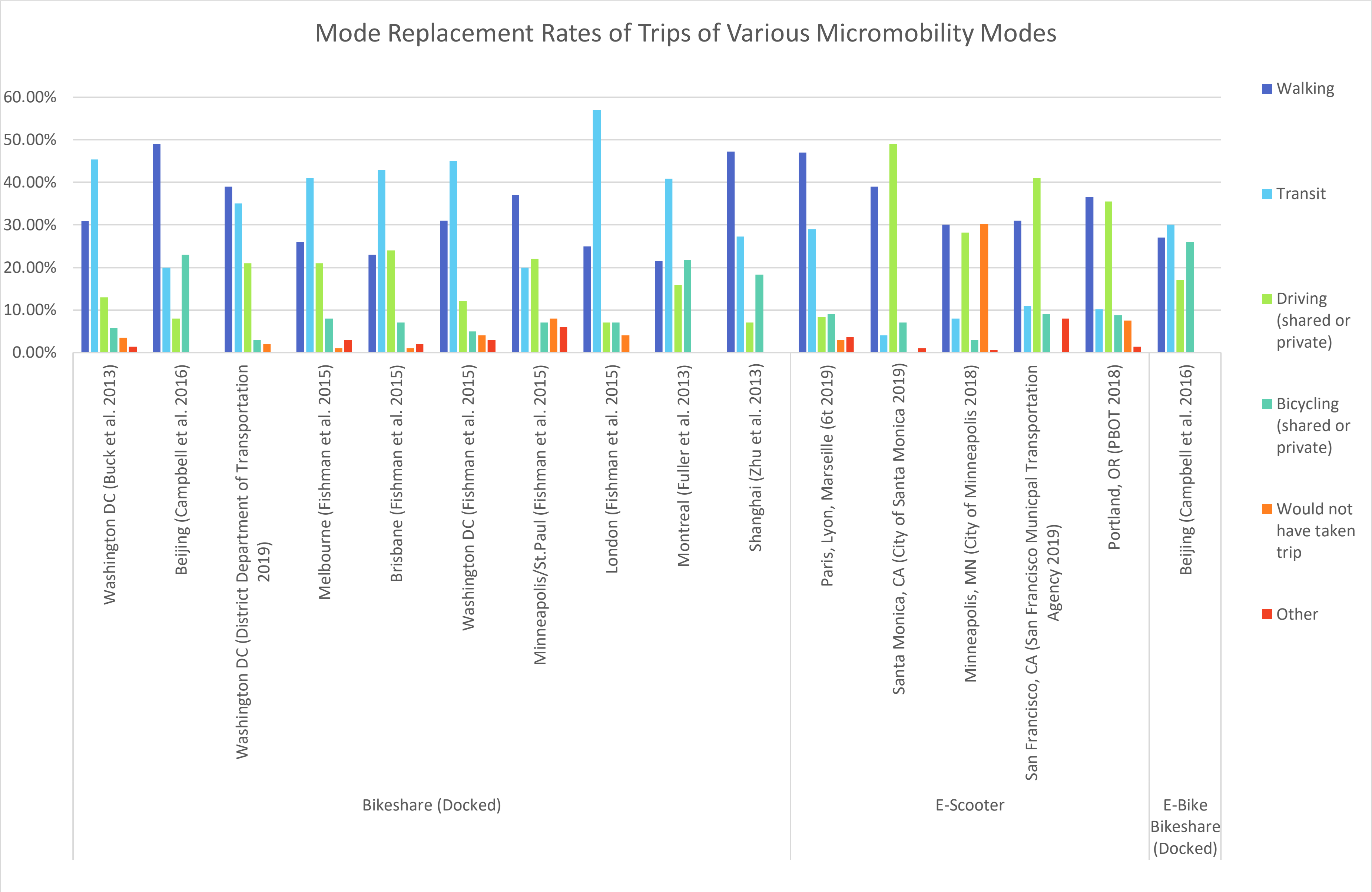

Figure 2: Mode Replacement Rates of Trips of Various Micromobility Modes

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