Cross-Country Comparison of Micromobility Safety, Built Environment and User Behavior

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Executive Summary

This report presents preliminary findings from four case studies on built environment and micromobility user behavior from safety perspective in San Francisco, San Jose, Singapore and Hong Kong. Based on field observation data in these four cities, supplemented by interviews and secondary data, it discusses the variations in terms of safety regulation, built environment, micromobility infrastructure, and user behavior across cities and countries. The cross-cultural comparison from human-centric and safety perspective set context for data-driven research on micromobility safety policy and infrastructure design.

Introduction

Despite a growing interest in studying micromobility such as e-bikes and scooters in recent years, few studies have focused specifically on user behavior and safety, not to mention comparative studies across jurisdictions. Due to lack of consistent data and complex policy context, previous studies on micromobility are better represented in North American and European countries which saw a rapid market penetration. However, micromobility is not completely new in some other countries, especially in Asia. For example, e-bikes and mopeds have long been prevailing in China and southeast Asia. *How does micromobility user safety behavior differ across countries and types of built environment and existing bicycle infrastructure?* This project aims to investigate this question through four case studies in four cities of the San Francisco Bay Area (San Francisco, San Jose) and Asia (Singapore, Hong Kong) with drastically different built environment and mobility landscape. The general understanding of difference in micromobility user behaviors and safety risks from a human-centric perspective in different built environment and policy contexts can potentially inform international standards and guidelines for micromobility safety policy and infrastructure design. This report summarizes preliminary findings from hundreds of hours of field observation data over multi-year fieldwork during 2022 in these four cities, supplemented by interviews and secondary data, and provides directions for future research.

In the following sections, I will first summarize previous literature on micromobility safety in terms of road infrastructure, user behavior, and their interrelationship, especially that with an international focus. Then, I will describe methods conducting this project and summary of findings for each case study. Finally, I will discuss policy implications and future research. It is hoped that future studies can build on this project and leverage emerging new data on built environment and micromobility user behaviors for data-driven research on micromobility safety policy and infrastructure design.

Previous Studies on Micromobility Safety

Micromobility safety is an emerging theme in transportation research, though there have been few empirical studies from safety perspective. For example, little is known about micromobility user behavior relative to other road users, and its safety risks on different types of road infrastructure. Empirical evidence is crucial to the understanding of the current status of road infrastructure amid the current micromobility surge, which could shed light on identifying the operational domain for micromobility vehicles, as well as to provide insight for proactive design guidelines that incorporates new mobility modes based on safety performance.

Previous studies on micromobility safety look into three major topics: safety regulation, road infrastructure, user behavior. The following sections will discuss each of these topics.

Safety Regulation

The most recent micromobility literatures concentrate in North America and Western Europe, though their focuses vary by geographic areas. Because regulations and guidelines are subject to local jurisdictions, scope and coverage of the studies are fragmented depending on the degree of local penetration. For example, empirical data of micromobility in the US are often drawn from a few cities such as San Francisco, Santa Monica, or pilot study areas like university campuses (City of Santa Monica, 2019; Maiti et al., 2020; Vision Zero SF Injury Prevention Research Collaborative, 2019a, 2019b). A more established stream of micromobility literature looks specifically at electric bikes in terms of trends, user perception and attitude in North America (MacArthur et al., 2014). Another major body of safety literature studies e-bike user behavior in China with more abundant data because of high market penetration.

Vehicle Classification

So far, there has been no consistent definition or classification of micromobility vehicles. Countries and cities across the globe adopt different standards to regulate varies emerging new types of vehicles featured by e-bikes and scooters. There is a fuzzy boundary between active modes (i.e., bike, walk) and micromobility, however this delineation could be essential in determining the operational domain and facility needs for micromobility. Moreover, even within the realm of micromobility states regulate types of devices differently (Fang et al., 2018).

One universal definition by SAE International (SAE International, 2019) specifies the criteria for powered micromobility vehicle in terms of curb weight (≤ 500 lb, 227 kg) and top speed (≤30 mph, 48 km/h), which exclude solely human-powered vehicles. It identifies six types of fully or partially powered micromobility vehicles including powered bicycle, powered standing scooter, powered seated scooter, powered self-balancing board, powered non-self-balancing board, and powered skates (Table 1). Some other international organizations set their own standards. For example, the New Urban Mobility Alliance (NUMO) developed an impact assessment tool for existing or hypothetical vehicle types based on maximum capacity, top speed, weight, space occupied, emission, and ILL-health metabolic equivalent (NUMO, 2020). Some adopt broader definition inclusive of human powered vehicles. The International Transport Forum proposed a micromobility classification scheme that consists of four types (A-D) by maximum speed, weight, and required physical activity (International Transport Forum, 2020, Table 2).

The only difference between this and SAE's definition is the inclusion of human-powered bikes, scooters and skateboards.

Table 1 Types of Powered Micromobility Vehicles (modified from SAE International, 2019)

	Powered Bicycle	Powered Standing Scooter	Powered Seated Scooter	Powered Self-Balancing Board	Powered Non-Self-Balancing Board	Powered Skates
Center column	Y	Y	Y	Possible	N	N
Seat	Y	N	Y	N	N	N
Operable pedals	Y	N	N	N	N	N
Floorboard/foot pegs	Possible	Y	Y	Y	Y	Y
Self-balancing	N	N	N	Y	N	Possible

Table 2 Proposed Micromobility Classification by ITF (modified from ITF, 2020)

	Type A	Type B	Type C	Type D
Power source	Unpowered or powered		Powered with top speed between 25-45 km/h (16-28 mph)	
Speed	< 25 km/h (16 mph)		top speed 25-45 km/h (16-28 mph)	
Weight	< 35 kg (77 lb)	35 - 350 kg (77 - 770 lb)	< 35 kg (77 lb)	35 - 350 kg (77 - 770 lb)
Example	Bicycle, E-bike, Standing scooter, E-scooter, Onewheel, E-unicycle	Mobility scooter, Cargo bike	E-bike, E-scooter, E-unicycle, Moped	Motor scooter

There appear larger discrepancies in definitions across countries (International Transport Forum, 2020). Some countries take more restrictive measures, while others are more open and flexible. For example, Singapore and Colombia designated e-scooters as a new vehicle category called personal mobility device (PMD), different from cars, bikes, or e-bikes; the European Union (EU) has an L-category in its vehicle standard. Korea stipulates the same rules for all micromobility vehicles as cars or motor vehicles. In China, e-bikes are classified as bicycles, a broad category of all vehicles under 25 km/h, 55 kg, with power under 300 W, battery voltage under 48 V (GB17761-2018). Mexico City sets 30km/h as the maximum speed for non-motorized vehicles. While e-bike and scooter are still subject to an open discussion in the US, they are predominantly regulated at state level. Despite the heterogeneity across contexts, most criteria are based on a combination of maximum speed, weight and power sources. The permitted speed for electric bicycles ranges from 20 to 30 mph (32 – 48 km/h) across states in the US. To differentiate from traditional human-powered bikes, the rest of paper will follow the SAE definition.

Operational Domain

As a result of ambivalent classification, there is no standard practice regarding where micromobility vehicles should operate or park. Right now, regulations vary by specific context. According to ITF (International Transport Forum, 2020), some countries or cities such as South Korea and Amsterdam, ban mopeds and most powerful e-bikes from bike facilities. In France and Germany, micro-vehicles users are required to ride on cycling facilities. UK and Ireland prohibited motorized micro-vehicles from public roads. Singapore bans e-scooters from footpath due to safety concerns (Toh, 2019). In the US, regulations are deferred to states. For example, in California, operation of e-scooters on sidewalks is prohibited (Vision Zero SF Injury Prevention Research Collaborative, 2019b); in Austin, Texas, scooters are allowed on both the sidewalks and streets (Tice, 2019).

In addition to right-of-way, parking regulation makes an important component of micromobility management concerning safety of riders and other road users. A study of scooter regulations in 101 US cities found 64% of them specify parking locations, among which sidewalks are the most frequency choice (39.7%) followed by against street furniture (20.6%) (Herrman, 2019). Brown et al. (2020) studied micromobility parking regulations in five US cities, Austin, Portland, San Francisco, Santa Monica, and Washington D.C., and found that motor vehicles (24.7%) impede access far more than bikes (0.3%) and e-scooters (1.7%). Based on such evidence, they argue cities should rethink parking policies considering all other technology-enabled transportation services. Meanwhile, Barbour et al. (2019)'s study suggests micromobility's parking locations still matter because of its interaction with pedestrians (especially pickup and drop-off) and other road users as well as the need to optimize parking locations and spaces.

Safety Data

Micromobility injury and fatality data are so far too scarce to draw meaningful conclusions. So far, there has been no consistent and comparable data collection protocol for micromobility or traffic safety data in general. Empirical research on micromobility safety mainly relies on two data sources, police and hospital reports, which are often subject to data quality and sampling issues. Crash reports in most countries do not separate new mobility categories. Moreover, there is often inconsistency and bias in either police or hospital reports. For example, pedestrian injuries are rare and under-reported in police reports with higher reporting rate of more severe injuries by hospitalization.

San Francisco is one of the first cities that responded to the data need of the emerging micromobility services (Vision Zero SF Injury Prevention Research Collaborative, 2019a). The city incorporated new vehicle classifications including e-bikes, e-scooters, moped, e-skateboard and hoverboard into hospital trauma records, to empirically track and understand new mobility-related injuries. Since 2015, it has adopted analytical approach using collision data to identify high injury network for vulnerable road users, particularly pedestrians and bicyclists (San Francisco Department of Public Health, Program on Health, Equity and Sustainability, 2017). Same method applies to collision and injury analysis specific to e-scooters (Vision Zero SF Injury Prevention Research Collaborative, 2019b).

The ITF report compiled a summary of data from various sources (e.g., media reports) on micromobility fatality and injury (International Transport Forum, 2020). Due to small samples or contextual differences, there comes up conflicting evidence. Nevertheless, it could at least provide us with a rough picture of general trend. According to ITF's estimate until the end of October 2019, most fatal and severe injury micromobility vehicle crashes involved a heavier vehicle, similar to the patterns of bicycle crashes, though fatality risks differ significantly across countries. In the US alone, NACTO estimates about 78-100 fatalities per billion e-scooter trips within a similar range of 21-257 per billion bicycle trips (International Transport Forum, 2020; NACTO, 2019a). The general risk is much lower than motorcycles and mopeds (132-1,164 per billion trips).

Most published studies on e-scooter injuries use data from California, which saw predominately male riders injured (City of Santa Monica, 2019; Vision Zero SF Injury Prevention Research Collaborative, 2019b), consistent with riders' demographics and high occurrence of risky behavior by male riders for other modes. Studies in Austin, St. Louis, and France all found that about half of e-scooter injuries are caused by road surface condition (6t-bureau de recherche, 2019; Austin Public Health, 2019; Haworth & Schramm, 2019; Petrin, 2019). E-scooter riders are less likely to wear a helmet than cyclists where obligatory (Haworth & Schramm, 2019; Trivedi et al., 2019). The body of literature on e-bike user behavior in North America, Netherlands and China agrees with such findings, in that e-bike users have higher levels of perceived safety but are also exposed to greater risks (Fishman & Cherry, 2016).

Cities regulate micromobility and its relationship with infrastructure by specifying the operational domain for each type of vehicle. Since vehicle classification is a vital determinant to the operational domain and other road safety regulations, understanding underlying factors such as speed, weight, and power source in relationship with built environment and infrastructure type could provide more specific guidance, for instance which type of users belong to which group in different circumstances. The Safe System Approach considers managing kinetic energy as an effective approach to safer roadways (Kumfer et al., 2019). This approach underscores two essential components of kinetic energy and corresponding vehicle characteristics, *mass* and *speed*, which aligns with the SAE classification (SAE International, 2019) (Table 3). Based on these two criteria, I examined the coupling effect between mass and speed across cities and countries where these numbers are specified in safety regulations. Figure 1 plots the relationship between vehicle weight and maximum speed limit corresponding to the kinetic energy formula ($E_k = 1/2mv^2$).

There is clearly a clustering of micromobility vehicle weight and speed limits, around the ITF type A classification. However, level of restriction varies across regions. Several countries and cities in East Asia such as Korea, Taiwan, and Hong Kong have most restrictive regulations that all power-driven vehicles regardless of weight and speed are considered as motor vehicles. Most other cities set limits around ITF's Type A boundary, at the maximum capacity of traditional active modes, particularly human-powered bicycles. The US and Canada adopt the least restrictive standard, with slightly higher speed limit than the most common 25 km/h. Despite the variation, regulations tend to focus on the interface between active modes and slow-light vehicles since the majority of micromobility vehicles are to share road space with other vulnerable road users (pedestrians and cyclists) whereas heavier or faster vehicles (Type B, C, D) are likely mixed with regular traffic flow. In this regard, regulations seem consistently conservative by grouping micromobility vehicles with non-motorized modes. Moreover, vehicle weight from kinetic energy point of view is less regulated than speed.

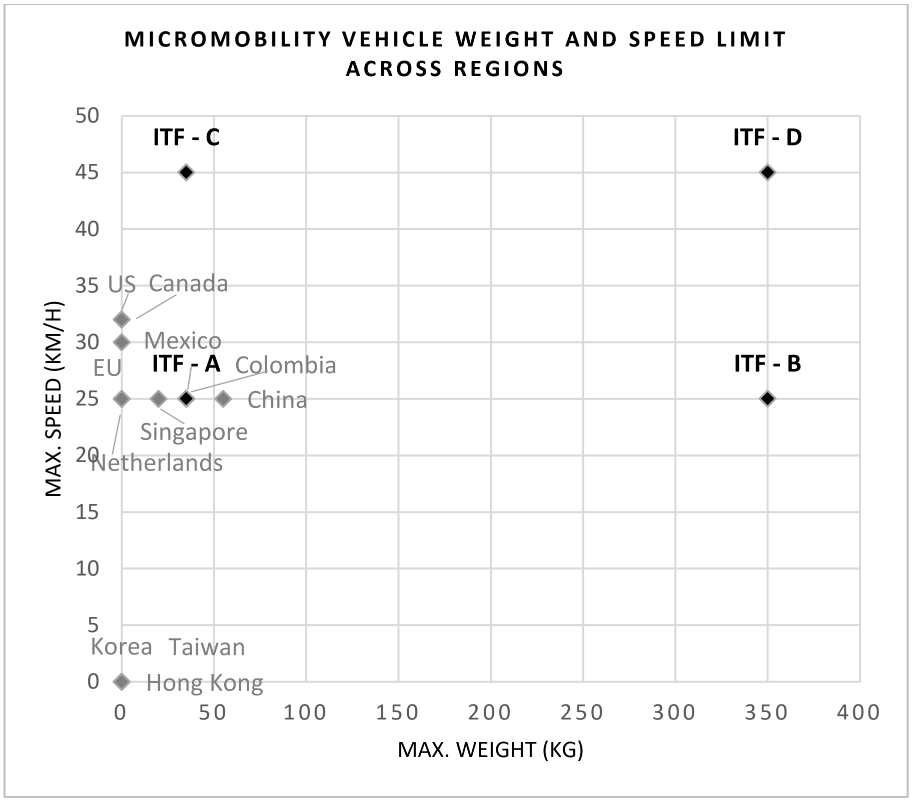
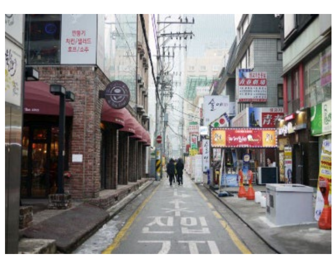


Figure 1 Vehicle weight and speed limit across regions (multiple sources)

Table 3 illustrates the typical built environment characteristics and road safety conditions of regions with least to most restrictive micromobility safety regulations. The Safe System Approach (Larsson & Tingvall, 2013) not only considers vehicle or micromobility user as the agent, but also incorporates local built environment, existing infrastructure, as well as safety performance into safety enhancement strategies. Once these factors are in place, the rationales under different safety regulations come to a more complete picture.

Table 3 Micromobility safety regulation and built environment

Safety regulation	Examples	Typical streetscape	Cycling infrastructure	BE characteristics	Road safety
Most restrictive	Korea, Taiwan, Hong Kong			High density urban environment with multimodal mixed traffic; narrow streets and limited cycling infrastructure	Moderate traffic fatalities, majority of deaths in non-car driver's categories

Most common	EU, Singapore, China, Mexico, Colombia			Medium density, diverse road users; adequate dedicated cycling infrastructure	A wide variance in road safety conditions
Least restrictive	US, Canada			Low density, mostly car traffic; relatively few dedicated cycling infrastructure	Relatively high traffic fatalities, majority of deaths in car-driver's category

Sources: Google Image, World Health Organization (2018)

Across countries, safety regulations are dependent on a series of built environment factors at multiple scales: building density, streetscape, roadway classification and configuration. Generally, in high density urban environment, for example those in East Asian cities, micromobility vehicles are often mixed with all other road users in narrow roadway spaces. These cities take cautious measures by imposing the same rules on micromobility vehicles and all other motorized vehicles, which significantly limits their interactions with heavy pedestrian flow. In cities with well-defined multimodal operational domains, the addition of micromobility vehicles has not yet changed the existing infrastructure, but often need compromise speed and weight to current users of cycling infrastructure. Particularly in the US and Canada where significant amount of road space is dedicated to cars, regulations on micromobility vehicles seem less restrictive, likely due to rare appearance or less perceived risk to other road users.

Road Infrastructure

The World Health Organization considers the lack of dedicated infrastructure as a poor road safety attribute and calls for design standards that specifically meet the needs of vulnerable road users (World Health Organization, 2018). Evidence shows that micromobility users are subject to similar or even higher level of risks than bicycle users (International Transport Forum, 2020). An Austin study found that 55% of micromobility incidents happened on the roadway, 1/3 on the sidewalk, while more than half of the injuries were associated with road surface condition (Austin Public Health, 2019; Tice, 2019).

Internationally, there exists no formal design guideline for micromobility infrastructure other than bicycle facilities. Although some of the safety countermeasures do not exclusively apply to bicycles, behavioral differences between bicycle and micromobility users suggest reconsideration of the road infrastructure. Some North American cities (Portland, Oregon and Atlanta, Georgia) made pioneering efforts adopting the Lite Transportation Lane, also known as Low Impact Transport (LIT) lane (International Transport Forum, 2020) to accommodate such need. In addition, a few other terms emerged that capture the speed and mass characteristics of micromobility vehicles, for example "slow lanes", "micromobility lanes", "third lanes", "BEST lanes" (Bikes Electric Scooter Transportation lanes).

National Association of City Transportation Officials (NACTO)'s *Guidelines for Regulating Shared Micromobility* is by far the most comprehensive guidelines that provides recommendations specific for micromobility infrastructure (NACTO, 2019b). It identified a few areas for consideration in public realm for micromobility vehicles, in particular, parking and safe place to ride. *"Cities should convene to discuss how street design standards may need to change to accommodate a wider array of low-to-moderate speed micromobility vehicles... cities may have to speed up implementation timelines for building high-quality bike infrastructure and consider how rising volumes will impact design specifications. In particular, engineers, planners and designers will need to consider what kinds of vehicles belong in bike lanes, and what factors (e.g., speed, rate of acceleration, maneuverability), should help determine what is allowed where."* It proposed a speed-based scheme for operational domains: unrestricted (15 mph), slow zone (5-12 mph), non-electric vehicle (0-3 mph), and prohibited space (user must walk vehicle). Although NACTO is the prominent standard in North American context, the huge disparity in quality of cycling infrastructure requires careful consideration across cities, especially across the world.

User Behavior

A majority of research that links micromobility user behavior and infrastructure adopts field observation approach. In China where e-bike riders along with cyclists constitute a large proportion of road users, studies were done to compare e-bike user behaviors with that of regular cyclists (Du et al., 2013). One particular area of interest is risky riding behavior such as speeding, red light infringement, and other road rule violations. Yang et al. (2014) observed more than 20,000 e-bike riders in Suzhou, China, and found a 38.3% rule violation rate when entering intersections, among which males are more likely to conduct risky behaviors. Among the 800 e-bikes with speed reading, 70.9% exceeded the designed speed limit of 20 km/h. The results are consistent with a similar study by Du et al. (Du et al., 2013). Small improvement in quality of infrastructure may enhance safety. For example, an observational study of 2,477 cyclists and e-bike riders in Hangzhou, China found a significant effect of sunshields in reducing red light infringement rate on both sunny and cloudy days (Zhang & Wu, 2013).

A few field studies emerged In the US as e-scooters began penetrating some cities. A recent one taking place at UT's San Antonio campus used pedestrian crowd-sensing to study the safety impact of scooters (Maiti et al., 2020). The large-scale field study from pedestrian's perspective helps to identify potentially unsafe zones by pedestrian/scooter encounter. Some other studies use simulation and neural network techniques to predict micromobility traffic and individual trajectory (Gavilan et al., 2019; Mohamed et al., 2020). These methods, by all means, provide information at network level, do not give many details on infrastructure design and its interaction with riders. Arellano & Fang (2019) observed 330 e-scooter riders in downtown San Jose, California and found differences in riding behaviors between e-scooter riders and cyclists, as well as those between riding on streets and sidewalks.

Several Dutch studies, for example van der Horst et al. (2014) apply the DOCTOR (Dutch Objective Conflict Technique for Operation and Research) conflict observation method to analyze video recording that captures traffic counts and interaction between user groups on bicycle paths. Specifically, the method first identifies a critical situation where available space for maneuvering is less than a regular situation, then assigns scores from 1 to 5 to the conflict based on 1) the probability of a collision, and 2) the extent of the consequences if a collision had occurred. Van der Horst et al. (2014) analyzed a total of 13.25 hours of conflict data for Amsterdam and 8 hours of conflict data for Eindhoven. Additionally, the researchers made classification on (light) moped behavior (e.g., free riding, overtaking bicyclists), measured speed of free-riding mopeds, and observed riders' gender, age, as well as lateral behavior in relationship with the available bicycle path width. Among all reviewed articles, this is the most comprehensive study focusing on individual user behavior, which gives insights into user behavior study by other modes, and in other contexts.

Summary of Previous Studies

On a local scale, human-centric infrastructure design relies on more granular understanding of safety risk and micromobility users' behavior. Whether it is for various jurisdictions to rethink operational domain or implement substantial design improvement retrofitting to new road users, individual behavioral research becomes crucial and feasible with assistance from new data and technology. Future research could build upon the methods developed by Arellano & Fang (2019) and van der Horst et al. (2014) to observe behavioral disparity between micromobility and other road users. I propose a framework that identifies potential injury hot spots for micromobility vehicles users and quantifiable measures to inform road infrastructure improvement.

As demonstrated, strategies to tackle micromobility safety issues on road infrastructure are twofold: **1) regulating the operational domain for each vehicle class; 2) retrofitting existing road infrastructure for new vehicle class through design**. However, both strategies require cities to have a better understanding of the existing regulatory framework and infrastructure before making substantial changes.

The delineation between active modes and micromobility, along with the classification between types of micromobility vehicles turns out essential to determine the operational domain and infrastructure needs for micromobility vehicles. Cities at the forefront of this wave of new mobility surge start to recognize such need (Vision Zero SF Injury Prevention Research Collaborative, 2019a). On the other hand, inconsistent definition and classification are likely due to heterogeneous road conditions and cycling infrastructure across cities, which in turn leads to ambiguous right-of-way and parking regulations. Discussions on standardizing vehicle classification and operational domain often overlook one important aspect of policy variations, especially across countries: built environment or more specifically existing infrastructure.

On infrastructure design, understanding the behavioral difference between bicycle riders and micromobility users, and how they interact with each other can help identify risks for both type of road users, informing proactive infrastructure planning and design. Studies suggest that riders who fall into the broad definition of micromobility users are more often associated with risky and aberrant riding behavior than bicyclists. Collisions and traffic injuries that involve micromobility users are more likely due to the riders themselves instead of other parties, and road surface condition, which implies that safety countermeasures should be focused on riders' behavior along with road surface improvement.

The emerging micromobility is a complex issue that requires more comprehensive understanding in terms of riders' behavior and infrastructure demand. Due to its nascency in US cities, more thorough and data-driven safety analysis is hindered by data scarcity. This not only calls for new data collection protocols, but also urges researchers to find innovative ways analyzing the data. On the other hand, granular data can help transportation professionals to assess the effectiveness of infrastructure improvement beyond network level, especially identifying measurable parameters to inform design.

Methods

In this study, I propose a research framework that incorporates built environment factors and Safe System Approach by analyzing large amount of field observation data collected from four cities across the US and Asia (i.e., San Francisco, San Jose, Singapore, and Hong Kong) in 2022, supplemented by interviews and secondary data. I analyzed safety-related measures including *operating speed*, *gap distance between riders*, *distance to the curb*, *point cloud*, and *potential conflict points* from video footage, and observe similarity and differences in user behaviors across geographic regions.

Case Selection

I selected two cities in the US and two cities in Asia (San Franisco, San Jose, Singapore, and Hong Kong) to include a diverse sample of cities in terms of built environment, local climate, and cultures. I then chose one urban location in each of the four cities as the observation site. All four locations are located in the central area of the city: 1) Market at 10th Street in San Francisco; 2) S 5th Street at Paseo de San Antonio outside San Jose State University in downtown San Jose; 3) Orchard Road outside the Apple Store in Singapore; 4) Hung Luen Road in Kowloon, Hong Kong. All of the observation sites have multi-lane multimodal traffic with dedicated pedestrian or bicycle access including sidewalk, crosswalk, and bike lanes. Table 4 presents the four field observation sites where I recorded videos throughout March and April 2022. Micromobility devices were observed in all locations though it was still considered amidst the COVID partial lockdown period.

Table 4 Field observation sites

City	Location	Date	Time	Description
San Francisco	Market/10th St	March 8th, 2022	1:30 – 2:30pm	Sunny weekend afternoon
San Jose	S 5th St/Paseo de San Antonio	March 4th, 2022	11:00am – 12:00pm	Cloudy noon outside SJSU campus
Singapore	Orchard Road in front of Apple Store	April 5th, 2022	11:10am – 12:10pm	Cloudy weekday noon
Hong Kong	Hung Luen Road, Kowloon	April 8-13th, 2022	AM, PM	Multiple days, mostly sunny days

Data Collection

At each site, I did at least one hour of observation recording the street-level activities while taking notes at around the same time of the day. All field observations were conducted during a non-rainy day at noon with moderate traffic. Video recording provides comprehensive time series data that capture user behavior from multiple dimensions, thus is a preferred tool for data collection. I took street-level videos that captured micromobility user activities with a GoPro device. I then analyzed the riding trajectory of micromobility users in the videos, as well as qualitative assessment of road safety conditions.

In the next section, I summarize the findings from each of the four field sites in terms of common and different characteristics of micromobility user behaviors, and their association with different built environment contexts.

Findings

Case Study: San Francisco

San Francisco is among the cities that set policy priorities for multimodal transportation including active mobility and micromobility as a new mode. My field observation site is located at Market Street, which has been "car-free" since January 29, 2020 as part of the Better Market Street program by San Francisco Municipal Transportation Agency (SFMTA). As a result, no private vehicle is allowed to travel in the car-free area that under this program (Figure 2).

Figure 2 Car-free area on Market Street, implemented January 2020 (source: SFMTA)

The observation site along Market Street is paved by sidewalks, and cycle tracks (Class IV protected bike lanes) on both sides (Figure 3, Figure 4). The reduced traffic made room for more dedicated pedestrian and bicycle infrastructure that attracts micromobility users by greater perceived safety. One the other hand, the street belongs to the city's High Injury Network (San Francisco Department of Public Health, Program on Health, Equity and Sustainability, 2017), meaning the location is more likely to observe conflicts between vehicles than other streets. I observed a variety of micromobility user types both at the intersection and road segment.

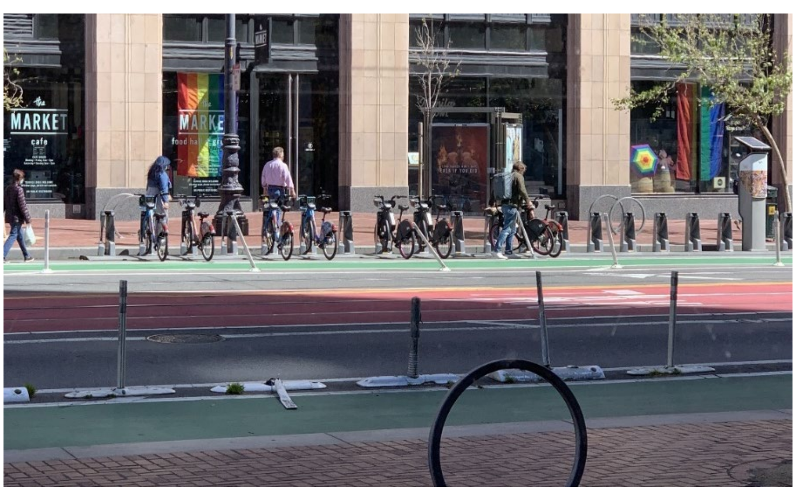


Figure 3 Observation site at Market Street, San Francisco (by author)

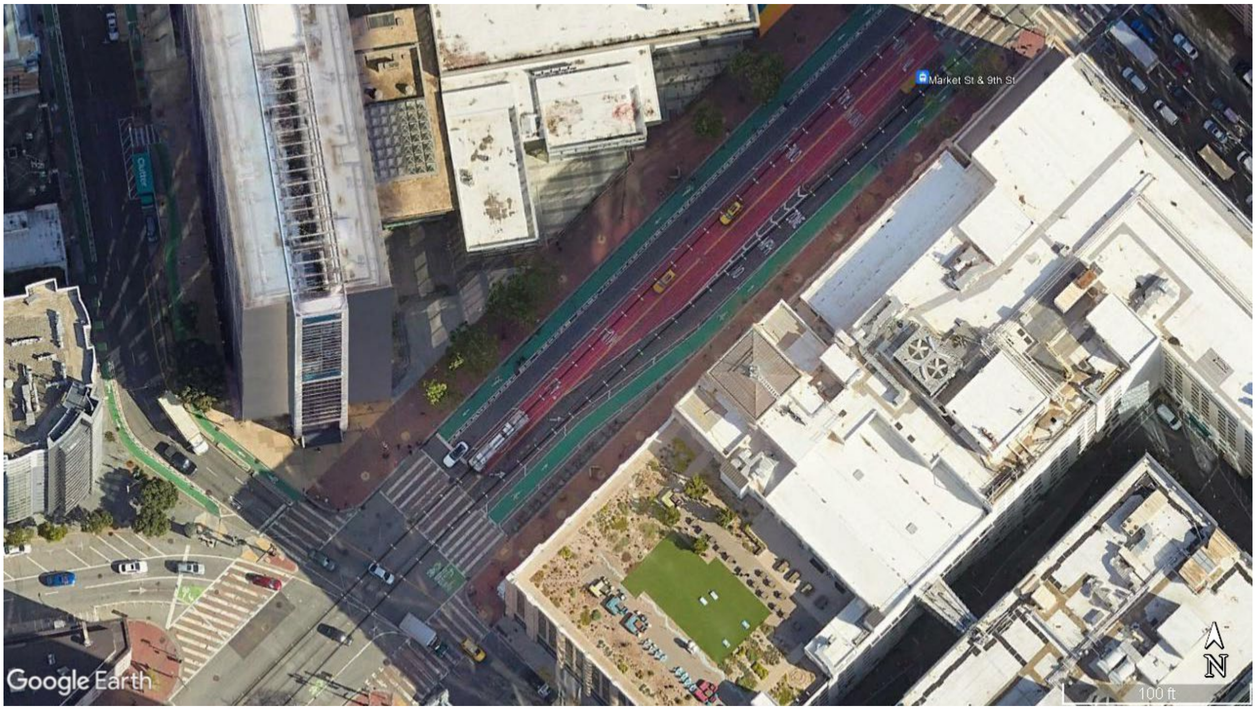


Figure 4 Market/10th Street, San Francisco (source: Google Earth)

Market Street served as a laboratory to observe a diverse range of micromobility user activities. On March 8th, 2022, a sunny weekday afternoon, it saw all kinds of micromobility in a one-hour period between 1:30 and 2:30pm. Very few cars were present on the segment since only vehicles with permit are allowed under the “car-free” Market Street scheme, whilst there is a wide variety of micromobility devices passing by within the hour. Table 5 shows the counts that I documented during the observation. Out of the 61 devices that showed up, a majority of them were e-bikes, standing or seated scooters. Other devices include skateboard and self-balancing board. Most of the riders wore a helmet while riding micromobility device, and a few skateboards rode in the opposite direction of the designated traffic flow, which poses some potential safety risks.

Per California Vehicle Code, it is illegal to ride a scooter on sidewalk. A majority of riders followed the traffic rule riding on protected bike lanes while some still operated on sidewalks.

Table 5 Count of micromobility devices in San Francisco

Micromobility device type	**Count**	**Operational domain**
Skateboard	4	1 sidewalk, 3 bike lanes
E-scooter	28	5 sidewalks, bilateral, bike lanes
E-bike	20	3 sidewalks, bike lanes
Seated scooter	7	bike lanes
Self-balancing board	2	bike lanes
Total	61	Majority on bike lanes, some on sidewalks

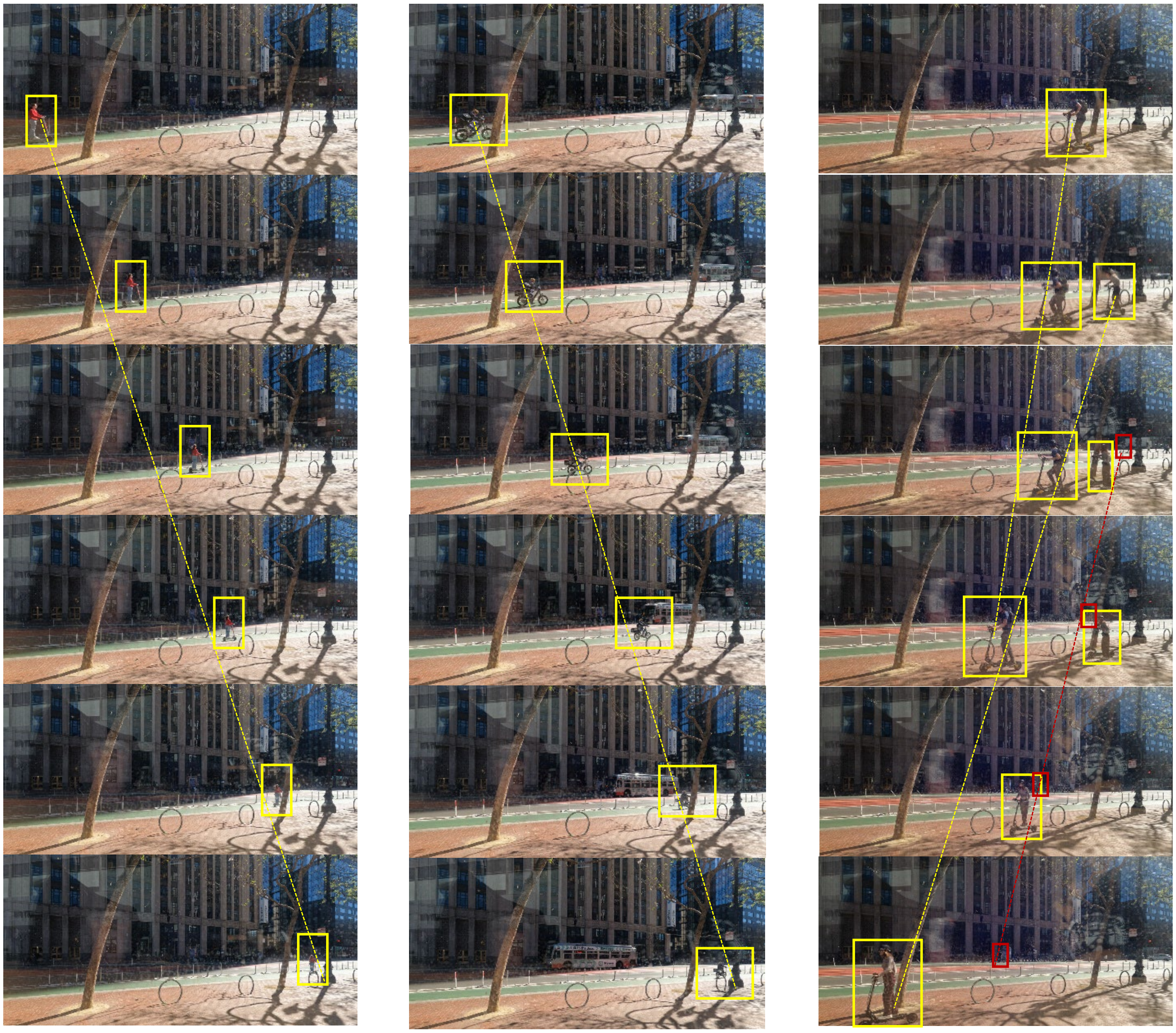


Figure 5 Trajectory of e-scooter and e-bike on protected bike lane, sidewalk, and crosswalk

Case Study: San Jose

Similar to the City of San Francisco, San Jose has implemented some micromobility pilot programs on top of its expanding bicycle network. The same traffic rule applies to prevent e-scooter and e-bike sidewalk riding. The location I chose was to the opposite of San Jose State University (SJSU) campus across a high-visibility crosswalk. Based on shared e-scooter ridership data provided by the city, S 5th Street is a major micromobility corridor with Class II parking buffered bike lanes on both directions and one-way traffic. The sidewalk is wide with plenty of space for street activities. Considering the popularity of micromobility among students, it was expected that the crossing would accommodate a large amount of micromobility activities.

Unexpectedly though, I observed only four such vehicles during the one-hour period, all of which obeyed the traffic rules (Table 6). Among the legal operational domains, skateboard riders opted for sidewalk rather than bike lane. The sidewalk was mostly occupied by pedestrians.

Table 6 Count of micromobility devices in San Jose

Micromobility device type	**Count**	**Operational domain**
Skateboard	2	sidewalk
E-scooter	2	bike lane, crossing
Total	4	

Figure 6 Observation site at S 5th St/Paseo de San Antonio, San Jose (by author)

Figure 9 S 5th St/Paseo de San Antonio, San Jose (source: Google Earth)


Figure 10 Trajectory of e-scooter on crosswalk


Figure 8 Trajectory of e-scooter on sidewalk

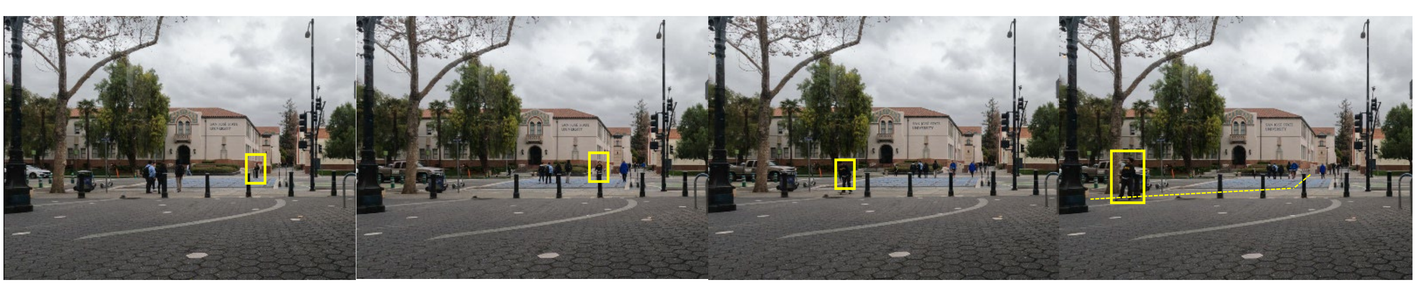


Figure 7 Trajectory of skateboard on crosswalk and sidewalk

Case Study: Singapore

Orchard Road is a major commercial street located in the Central Area of Singapore. Since it is among the top tourist attractions, it attracts all kinds of visitors that form a vital public realm (Figure 11). The field observation was conducted during the one-hour period between 11:10am and 12:10pm on a cloudy Tuesday along the sidewalk and main road in front of a store. Orchard Road is a four-lane two-way street with heavy mix-flow traffic. It has wide sidewalk space for pedestrians but no dedicated bike lane (Figure 15).

Per Singapore's traffic law, e-scooters (personal mobility device) are banned on roads or sidewalks but cycling/shared path due to safety concern. However, motor scooters (mostly delivery services) were commonly seen on motor vehicle lanes. During the one-hour observation on Orchard Road, I observed plenty of motor scooters and bikes on vehicle lanes, as well as some bikes and slow micromobility devices on the sidewalk. Additionally, I did two one-hour observations in cycling and shared path at Marina Bay and Esplanade respectively (Figure 12).

Figure 12 Example of cycling path and shared path in Singapore (by author)

Figure 11 Observation site at Orchard Road (by author)

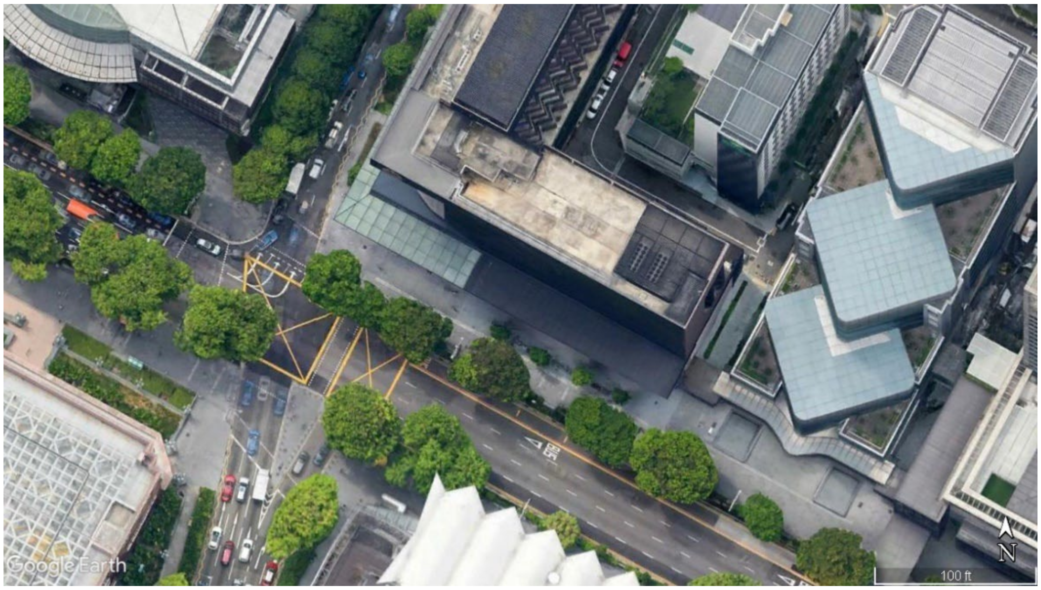


Figure 15 Orchard Road in front of Apple Store (source: Google Earth)

Figure 14 Motor scooters on Orchard Road

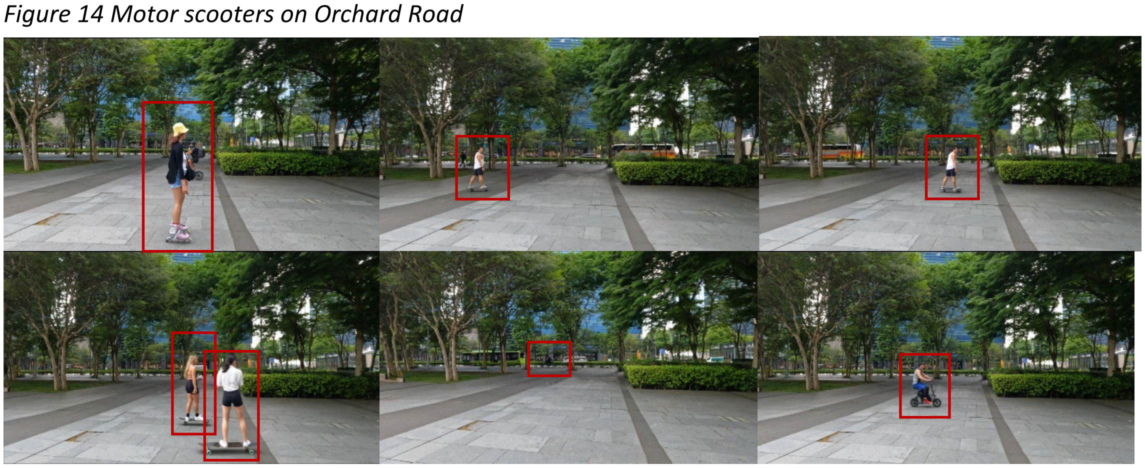


Figure 13 Micromobility (PMD) at Esplanade

Case Study: Hong Kong

Hong Kong was the second Asian case in this study. The field observation was conducted during multiple days between April 8 and 13th, 2022 at Hung Luen Road, in Kowloon, Hong Kong. Due to the COVID partial lockdown, there was moderate traffic on the four-lane street located close to the Harbor and an elementary school, which includes a crosswalk location connecting sidewalks on both sides of the street (Figure 16, Figure 17). Motor scooters, mostly for food delivery services, passed by frequently, so did some bicycles and scooters.

Hong Kong's scooter policy has gone through several ups and downs. By the time this field work was done, electric mobility devices including e-scooters were banned on roads, footpaths or cycle tracks in Hong Kong (Figure 19). Recently in April 2023 however, the city launched a pilot program to allow e-scooters on some cycle tracks with speed limits, as part of its green transport effort.

Figure 16 Observation site at Hung Luen Road, Kowloon (by author)

Figure 17 Hung Luen Road, Kowloon (source: Google Earth)

Figure 19 Banner reads "Electric Mobility Devices are banned on roads (including footpaths)" (by author)

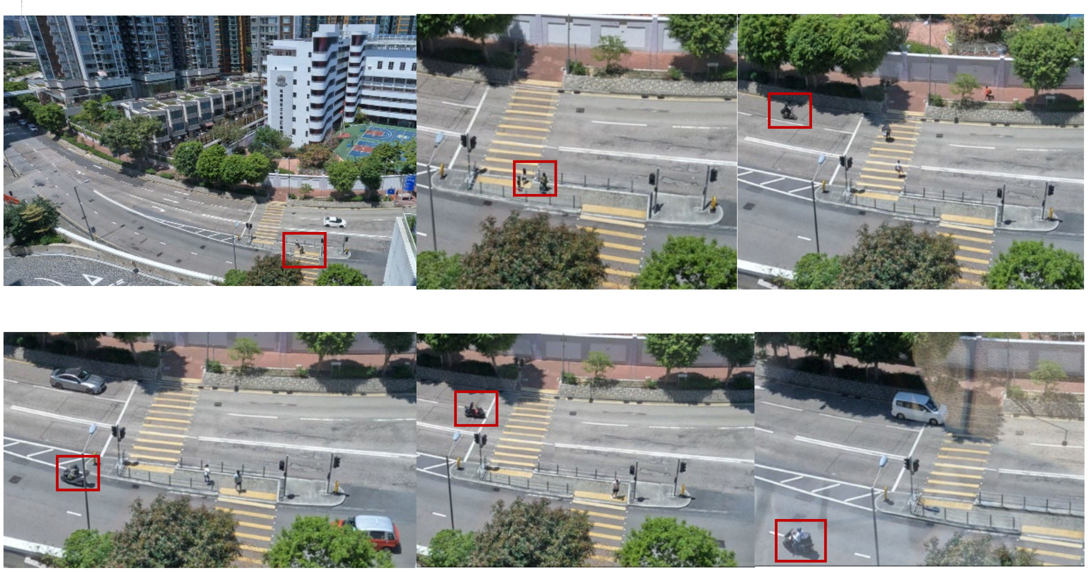


Figure 18 Micromobility on crosswalk and Hung Luen Road

Discussion and Conclusion

In this study, I propose a framework based on multi-site international fieldwork to compare safety regulations and micromobility user behaviors across different cultures and built environments. It is found that safety regulations regarding micromobility's operation domain has been relatively consistent between cities with similar built environment typologies. Specifically, in both US cities, e-scooters and other PMDs were allowed on roads with certain speed limits, while Asian cities adopted more conservative policy completely banning e-scooters in public domain except for some dedicated areas like cycling or shared paths due to safety concern. Nevertheless, there seem to be more safety violations such as riding on the opposite direction or on the sidewalk in San Francisco and San Jose, even though they had looser micromobility regulations, which is likely due to the larger number of micromobility users in these cities. Regardless of traffic law, users tend to choose the safer operational domain available, but also depending on perceived safety condition. For example, comparing San Francisco and San Jose where traffic rules were similar and e-scooters were banned on sidewalks, micromobility users were more likely to ride on sidewalks where no protected bike lanes were available. Most users in both the US and Asia wore helmets.

Because of the short timeframe, this study has only conducted preliminary assessment of potential consistency and divergence in micromobility safety and user behavior. Another drawback of this study is data collection during the COVID-19 period, which limited the sample size due to reduced traffic. Since micromobility as a new mobility mode is still developing over time, the patterns revealed by this study only represent a snapshot of the policy and behavioral landscape across the world.

Nevertheless, qualitative exploration provides directions to more focused analysis in risky factors so as to inform specific policy suitable for local context. Future research could scale up the number of observations and sites by utilizing user-generated mobility data to observe individual user characteristics and movement patterns, as well as applying computer vision technology to automate large-scale built environment feature detection. Quantitative data can be combined with other safety and built environment data to assess the policy impact on micromobility safety across contexts. For example, specific design parameters might affect micromobility user behaviors differently in different built environment contexts. Individual level collision data that involves micromobility users would be particularly useful in determining built environment features with potential safety risks. Moreover, local climate conditions also need to be considered as a factor that differentiates user behaviors.

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