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RESEARCH-ARTICLE

## Security and Privacy Challenges in Upcoming Intelligent Urban Micromobility Transportation Systems

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# Security and Privacy Challenges in Upcoming Intelligent Urban Micromobility Transportation Systems

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## ABSTRACT

Micromobility vehicles are gaining popularity due to their portable nature, and their ability to serve short distance urban commutes better than traditional modes of transportation. Most of these vehicles, offered by various micromobility service providers around the world, are shareable and can be rented (by-the-minute) by riders, thus eliminating the need of owning and maintaining a personal vehicle. However, the existing micromobility ecosystem comprising of vehicles, service providers, and their users, can be exploited as an attack surface by malicious entities – to compromise its security, safety, and privacy. In this short position paper, we outline potential privacy and security challenges related to a very popular urban micromobility platform, specifically, dockless battery-powered e-scooters.

## CCS CONCEPTS

- **Human-centered computing** → *Ubiquitous and mobile devices;*
- **Computer systems organization** → *Embedded and cyber-physical systems.*

## KEYWORDS

Micromobility, e-scooters, security, privacy.

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## 1 INTRODUCTION

Micromobility has emerged as a popular mode of urban transportation and collectively represents the compact, lightweight vehicles such as electric scooters, electric skateboards, electric bikes, hoverboards, etc. [17]. Among these vehicles, electric scooters or e-scooters are the most appealing to urban users [36], mainly due to the shared or rent-by-the-minute schemes offered by a number of different service providers. These vehicles are preferred by users for a plethora of reasons, such as their portable nature which allows easier bypassing of urban traffic, and their ability to reach destinations that otherwise required walking [33]. While the docked models can be parked at fixed locations, the dockless models can be dropped off at a more flexible location. The most noteworthy aspect is their potential to connect the gray area between traditional points-of-interests such as parking lots and bus stops, and final destinations such as workplaces and campus buildings, in congested areas or places with limited transportation. These convenient options also save users from maintenance costs associated with owning a vehicle, and from rather expensive ride-hailing or ride-sharing costs for short distance travels. Further, the streamlined process of geo-locating nearby scooters through the service provider's application, easy payment options, and flexible drop-off or parking options make micromobility e-scooter services notably attractive to urban commuters.

The electric scooter adoption has either been a success (coexisting with existing modes) or a failure (creating chaos) in urban communities depending on the readiness of the cities to these unconventional transportation means [2, 4, 13, 18]. Shared electric scooters deployed by the service providers, such as Lime and Bird, are almost universally equipped with an embedded controller and can be activated using their corresponding smartphone application [3, 6, 11, 23]. The scooters communicate with the smartphone application using BLE (Bluetooth Low Energy) spectrum and/or using the Internet, both of which are well established and prevalent technologies. However, the use of such communication channels also opens the door to a plethora of attacks, some of which can be especially effective on micromobility e-scooters. Similarly, the use of cloud for managing the e-scooter rental and user data can become a lucrative target. The literature is already rich with various

different attacks on micromobility e-scooters, and some of these resources are readily accessible online [12, 20, 22]. Amateurs without expert knowledge or grasp of the underlying technology can easily adopt and execute (with reasonable success) these attacks for monetary or other gains, with only slight modifications of existing tools and techniques.

While some of the attacks have already been addressed, many remain unaddressed either due to lack of a suitable solution or due to lack of awareness. Moreover, while many different attacks are already published, no prior work systematized the various attack points within the micromobility ecosystem and the different types of adversaries. In this paper, we systematize and discuss security and privacy concerns pertaining to the micromobility e-scooter services, along with attack scenarios plausible with their interfaces that may exist or may have been exploited. Such a systematic discussion will help developers and researchers to easily identify weaknesses, and improve overall security and privacy properties of the ecosystem. We also discuss potential countermeasures against some of the attacks, wherever possible. Before describing the different attacks in Section 3, we first detail the micromobility e-scooter service ecosystem in Section 2.

## 2 BACKGROUND

Micromobility e-scooter users can access the shared vehicles via the smartphone application provided by the service providers. First, the rider creates a user account and register a payment method with the service provider. The rider can then skim through a list of nearby e-scooters through the application, and navigate to the desired e-scooter. Once in close proximity, the rider scans the QR code on the e-scooter, initializing the riding process and starting the e-scooter both contingent on the funds (credits) and charge remaining on the e-scooter battery. The service providers charge from 15 to 30 cents per minute to ride the e-scooter along with a base activation fee. Certain e-scooter models can travel up to a distance of 28 miles in a single charge, which is much shorter than the average distance covered in e-scooter trips [31]. The e-scooters can reach speeds up to 18.6 miles per hour in a typical ride based on the road conditions and other vehicle traffic, and are equipped with headlights, tail or brake lights, a bell or horn and sometimes a display. While some models have throttle and front brakes located on the handlebar similar to a motorcycle, other models have foot-controlled brakes or rear disk brakes or anti-lock brakes for a safer ride [3, 6, 11, 14, 15, 23].

E-scooters primarily rely on BLE communication, which broadcasts packets at fixed intervals that can be captured by smartphones. These packets contain unique identifiers which help in identifying the e-scooters from other BLE devices. To start or stop most e-scooters, the operating smartphone needs to have both Bluetooth enabled and Internet data available by means of a wireless WAN such as Satellite or 3G/4G. This can be easily tested by toggling both the options on and off and checking if the e-scooter can be started or stopped with only one of the features. Overall, the important entities that are part of the micromobility infrastructure are the rider, the smartphone used by the rider to communicate with the e-scooter, the offline (BLE) and online (cloud) communication medium used by the service providers, and the e-scooter itself. The

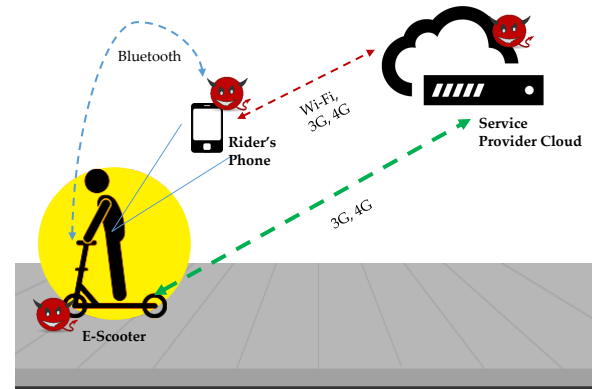


Figure 1: E-scooter ecosystem and attack points.

attacker or adversary, active or passive, in a micromobility ecosystem can be a *rider*, an *outsider* or the *service provider* as shown in Figure 1.

A **rider** can manipulate the e-scooter and the service provider for personal benefits by exploiting vulnerabilities in the smartphone application and the communication channels. An **outsider** can be any third party entity with harmful (or deceptive) intentions towards the rider or the service provider or an entity who may be curious about the micromobility ecosystem or the rider. The outsider can attack the e-scooter, the rider, the communication channel or the service provider. The **service provider** can obtain information about the micromobility users and their surroundings in addition to e-scooter operations. As a result, the service provider may constantly monitor user habits and preferences and share sensitive information with third parties to maximize revenue. These entities cause various hazardous scenarios and privacy concerns that affect the micromobility e-scooter ecosystem intentionally or unintentionally. A comprehensive set of security and privacy concerns are systematically described next.

## 3 POTENTIAL ATTACKS

### 3.1 Physical Damage

**3.1.1 Observations.** The key components in the e-scooters are its battery, engine, brakes, headlight, controller chip and other mechanical, electrical and electronic components to ensure the safe and smooth driving experience for the rider. Some e-scooters also have anti-theft mechanisms in place such as physical locks that can be enabled and disabled from the rider's smartphone through BLE. They may also have alarm systems that emit loud sounds or frequent beeps in the event they are displaced without unlocking them. Any of these components can be the target of an attacker and often times the e-scooter itself. For instance, e-scooter brake wires and batteries were targeted in several physical attacks [7]. E-scooters were also stolen and possibly used as a personal e-scooter by flashing custom firmware on the e-scooter controller [9, 10, 19].

**3.1.2 Consequences.** An attacker (the rider or outsider) can target the e-scooter battery, specifically drain it before attempting to move or acquire it, in order to circumvent the security mechanisms. Once the e-scooter is acquired, the attacker can install malicious

modules, remove or replace key components before placing it back in the streets to control the e-scooter remotely or to covertly gather data about the e-scooter and populace near the e-scooter. These tampered e-scooters can be a threat to road users in many ways. An attacker can intentionally injure the victim rider by remotely manipulating or interfering with the e-scooter's brakes, damaging the tires or other physical damage that could incapacitate the e-scooter. An attacker can indirectly target a group of non-riders or other vehicles on the road by strategically targeting a rider in their path. Such attacks cause a monetary loss for the service providers, environmental pollution (when burned by vandals), and physical damage to road users. An attacker, with financial interests, can sell the untraceable (removing key identifiers) or modified (malware) e-scooters online, which can later be converted for personal use [9].

**3.1.3 Countermeasures.** The service providers could assign the e-scooter chargers (users tasked with charging the e-scooters for a small payment) an additional task of checking the vital functionalities of the e-scooters such as brakes and tires before redeploying them after charging. Further, the non-riders and other road users who come across any issues in the e-scooter could have an option to report them allowing the service provider to take it out of service in order, thus preventing any other user from riding it.

## 3.2 Eavesdropping

**3.2.1 Observations.** The e-scooter communicates with the rider smartphone application over the BLE channel, and alternatively over the Internet. Some applications transfer data over a secure channel(s), which makes it nonviable for an entity to view its contents but it is still feasible to analyze the data flows and infer the application's behavior akin to [35]. However, most applications do not encrypt data before transmission, so entities can listen to data exchanges between the e-scooter and rider smartphone over these channels with suitable hardware (Ubertooth) or software (Wireshark).

**3.2.2 Consequences.** The ability to successfully sniff control commands and service requests can give leverage to an attacker, active or passive, to study the micromobility e-scooter ecosystem when combined with fuzzing and to explore a world of exploitations described in Sections 3.3 and 3.4. For instance, researchers in [24] identified Bird's API endpoints that contained the QR code information used to reserve e-scooters and make them chirp without being in physical proximity to the e-scooter. Also, the leakage of the e-scooter lock information from the API shows the possibility of attackers stealing them without draining e-scooter batteries.

**3.2.3 Countermeasures.** It is difficult to deter entities from sniffing data, nevertheless the service provider should design the applications and services to prevent sensitive information leakages and hinder exploitations by disabling or making key features inaccessible to unauthorized entities, and by employing appropriate cryptographic solutions wherever applicable.

## 3.3 Man-in-the-Middle and Replay Attacks

**3.3.1 Observations.** With sufficient knowledge obtained from the eavesdropping attack, an attacker can intervene (modify commands

or drop data) communication between a rider smartphone and an e-scooter. BLE vulnerabilities have allowed researchers to perform MITM attacks on the Xiaomi M365 e-scooter [5, 16, 25].

**3.3.2 Consequences.** The ability to successfully replay or mimic a rider opens up the possibilities of attacks described in Section 3.4. An attacker can jam the communication medium by bombarding with multiple legit or malformed requests (replay) in a short time period for a Denial-of-Service or fuzzing based attacks, ultimately exhausting e-scooter battery. An attacker (with malicious intent towards the rider) can control the e-scooter by injecting commands remotely, and intentionally cause physical harm to the rider and other road users alike.

**3.3.3 Countermeasures.** The attacks can be mitigated by preventing eavesdropping (Section 3.2), by observing the behavior of the nodes and the nature of their packet requests and blacklisting suspicious nodes [26, 29]. Furthermore, the service providers and micromobility users should consider keeping their services and smartphones updated to patch up any security vulnerabilities.

## 3.4 Fuzzing and Denial-of-Service

**3.4.1 Observations.** With the ability to sniff and mimic application traffic, an attacker (even those with limited knowledge of the system) can gauge how each service provider's firmware, application, and other control systems react to random or fuzzy data and therefore identify new vulnerabilities that could not be found through passive eavesdropping alone. The attacker (a rider or an outsider) can then leverage the observed flaws and construct malformed payloads to manipulate or disrupt micromobility services. Denial-of-service (DoS) attacks, enable by fuzzing, can constitute a cluster of attacks that has the ability to disrupt micromobility services in different forms, such as unauthorized locking and unlocking of the e-scooter, rapid resource exhaustion on the vehicles, or degrading quality-of-service in general.

**3.4.2 Consequences.** An attacker (rider or outsider) can infer the protocols used, authentication information (e.g., e-scooter password) and service request-responses by the application by passively eavesdropping or sniffing traffic and actively testing the system, and may be able to intercept, manipulate or replay the requests. While an attacker can identify (publicly available) nodes leaking sensitive information, the attacker can also leverage the applications that may be using extraneous permissions by covertly exploiting it to collect information, track the user and access other non-micromobility related services. Combined with the findings from Section 3.2, an attacker can implement this attack on a massive scale.

**3.4.3 Countermeasures.** The service provider can control fuzzing and DoS attacks by preventing eavesdropping and MITM attacks (Sections 3.2 and 3.3), systematically monitoring and filtering real-time traffic, maintaining logs and implementing disaster recovery plans for quick recovery in the event of an attack [38, 40].

## 3.5 Spoofing

**3.5.1 Observations.** The micromobility applications track the location of the e-scooter using the inbuilt Global Navigation Satellite System (GNSS) module onboard the e-scooter or using the rider's

**Table 1: User data collected, according to the privacy policies of various micromobility service providers.**

Service Provider	User Provided				Automatically Collected			From 3rd Party Sources
	Contact Info	Billing Info	Identification Info	Demographic Info	Device Info	Location and Vehicle Info	Analytics	
Bird	✓	✓	✓	✓	✓	✓	✓	✓
Lime	✓	✓	✓	✓	✓	✓	✓	✓
Razor	✓	✗	✓	✗	✓	✓	✓	✓
Lyft	✓	✓	✓	✓	✓	✓	✓	✓
Jump	✓	✓	✓	✓	✓	✓	✓	✓

smartphone or both. An attacker, the rider or the outsider, can target either to manipulate this location. In the first approach, the rider can install any location spoofing applications (available on the Internet) on the smartphone to fake their location [1, 8, 41]. After installation, the rider can easily trick the micromobility application and the service provider. In the second approach, an attacker can manipulate or replay GPS signals using SDR hardware (HackRF, USRP, BladeRF, etc.) which can produce and broadcast forged GPS signals to the victim receiver. It is also possible for an attacker to capture a GPS signal from a different location and rebroadcast it to the victim receiver (replay attack) [39]. The latter approaches can trick both the GNSS modules on the smartphone (solely reliant on GPS for location) and the e-scooter.

**3.5.2 Consequences.** A successful location attack gives an attacker the ability to manipulate the application and navigate the victim who depends on GPS navigation into dangerous situations or locations. For instance, an attacker with malicious intent towards the victim can strategically select and spoof the location of an e-scooter(s) to a secluded area or an area with minimal human presence to entice the victim riders. An attacker with the intent of financial gain can follow a similar approach to spoof the e-scooters to a randomized location (or physically hide in plain sight) making it difficult for riders (and e-scooter chargers alike) to find them, leading to financial loss for the service provider. Indirectly, this approach eventually leads to a drained and/or probably stolen e-scooter, and increases the bounty for finding that e-scooter, thus making it a profitable venture for the attacker (e-scooter charger). An attacker (who may be operating as a rider) may also be able to park in restricted or geo-fenced areas or no parking zones, thereby causing a public nuisance.

**3.5.3 Countermeasures.** To prevent location spoofing, the GNSS module should not solely rely on GPS but also use additional sources for location determination [32, 34, 37]. The GNSS module should also have provisions for location spoofing detection.

### 3.6 User Data Sharing and Inference

**3.6.1 Observations.** User data in micromobility platforms can range from any smartphone related activity to a history of locations the rider has visited for any period of time. Moreover, micromobility service providers often share user data with third parties, such as advertisers and city planners. Table 1 lists the different user data collected by popular micromobility applications, as disclosed in their privacy policies. Most of these applications share aggregate data with third parties and require constant location updates during a trip, and therefore have access to very sensitive information (e.g., users’ residence and workplace locations). Other data categories

and corresponding issues are yet to be explored, and they can vary across service providers.

**3.6.2 Consequences.** Unregulated and non-anonymized data sharing can be used to create a user profile that can later compromise user safety [21, 30]. A malicious party can mine the data obtained from either the service provider or through eavesdropping to infer more information about the micromobility service users and neighboring people. For instance, an attacker (application with intent of financial gain) can discover neighboring users in the vicinity via BLE, users in the house via WiFi devices, and use other phone activity usage information to know more about the rider (and user) and his surroundings. An attacker (other stakeholders) can use the information to learn about the users and then strategically place e-scooters on road, entice riders with suitable social media advertisements, etc. An outside attacker with malicious intent may also be able to monitor the victim’s schedule with the location history and be able to identify rider preferences, frequency of visits, and use the information for personal vendetta and financial gain, spreading the information to other malicious entities, who could track the user down in person effectively be a physical threat to the users.

**3.6.3 Countermeasures.** Privacy compliance defines how a company conforms to privacy laws, policies, guidelines in different countries or regions when managing confidential personal data [28]. An extensive analysis, with existing approaches and techniques such as inferring traffic flows of the applications [27, 42], is required to check if micromobility services have any information leakages and adhere to what they promise to collect or do with the collected sensitive user data. In addition to this, the data stored by service providers and shared with third party entities for analytics purposes should be privacy preserving (sanitized and free from personal identifiers) to prevent any inference attacks on the micromobility service users and their surroundings.

## 4 CONCLUSION

After describing the various components in the micromobility e-scooter ecosystem, we systematically summarized critical security and privacy concerns in the ecosystem, which both the micromobility users and service providers should be aware of. This first-of-its-kind systematized discussion shall be helpful to developers and researchers for identifying new weaknesses and improving the overall security and privacy properties of the micromobility e-scooter ecosystem. Given the constant evolution and changes in the applications and services, we intend to extensively analyze the ecosystem again in the future.

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