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A smart mobility game with blockchain and hardware oracles

Behzad Maleki Vishkaei [a], Pietro De Giovanni [b,c,*]

[a] Department of Management and Technology, Bocconi University, Milan, Italy
[b] SDA Bocconi School of Management, Milan, Italy
[c] DIR—Claudio Dematté Research Division, Sustainable Operations and Supply Chain Monitor, Milan, Italy

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ABSTRACT

This research examines smart mobility, specifically focusing on e-scooters as a mode of urban transportation. It underscores the advantages of e-scooters in smart cities while also addressing the issues stemming from incorrect riding practices. To understand the strategies of both cities and e-scooter companies, the study adopts a game theory approach. The research delves into how blockchain technology and hardware oracles can promote the appropriate use of e-scooters. In one scenario, the city allocates resources to infrastructure to facilitate e-scooter travel, while the e-scooter company defines its service. Nonetheless, continuous misuse of e-scooters negatively impacts both parties. Therefore, in another scenario, the research assesses how blockchain can detect and penalize incorrect behaviors using smart contracts. The findings reveal that while blockchain bolsters smart mobility and curbs the incorrect use of e-scooters, it might also dissuade certain users from utilizing the service, presenting a set of challenges to smart mobility.

1. Introduction

In today's rapidly evolving urban landscape, the concept of smart mobility has emerged as a powerful catalyst for transforming cities into more sustainable and livable environments. As the global population gravitates towards urban centers at an unprecedented rate, cities are confronted with critical challenges, including traffic congestion, air pollution, and inadequate transportation infrastructure (Demir et al., 2014). In light of these pressing issues, there is a growing recognition of the need to complement traditional urban transportation systems with the realm of shared mobility. The latter, encompassing services such as carpooling, ride-hailing, bike-sharing, and e-scooter-sharing, holds immense potential to address the multifaceted challenges faced by cities today. In fact, shared mobility initiatives can optimize the utilization of existing transportation resources, reduce the number of privately-owned vehicles on the roads, and alleviate traffic congestion (Machado et al., 2018; Zhou et al., 2023). However, these sharing mobility systems that are becoming the essential components of the urban transit infrastructure require more investigation in terms of various control policies like improving the pricing policy and increasing usage numbers (Soppert et al., 2022), fleet management policies like relocating and redistributing the vehicles considering level-of-service and capacity constraints (Nair and Miller-Hooks, 2011), and engagement of citizens and city transportation agencies (Hasija et al., 2020).

Among the various shared mobility systems, people have been using e-scooters more frequently than before in recent years, generating increasing interest among academia and scholars, as well as stakeholders, firms, and policymakers. One of the primary advantages of adopting e-scooters is the improvement in urban mobility. E-scooters offer a convenient and flexible mode of transportation, particularly for short-distance trips. They can efficiently navigate through congested urban areas, providing a practical last-mile connectivity solution. By complementing existing public transportation systems, e-scooters can bridge gaps in connectivity, reducing travel times and enhancing overall mobility options for residents and visitors alike (Wang et al., 2023). Cities worldwide are increasingly focusing on sustainability goals, aiming to reduce greenhouse gas emissions and alleviate traffic congestion. E-scooters contribute to these objectives by offering an eco-friendly transportation alternative. As electric vehicles, they produce zero tailpipe emissions, thus minimizing air pollution and mitigating the adverse environmental impacts associated with conventional petrol-powered vehicles (Bai and Jiao, 2020). By offering an alternative to private car usage for short trips, e-scooters help reduce the number of vehicles on the road, resulting in smoother traffic flow and decreased congestion. Additionally, the compact size ensures easy parking, requiring less space compared to traditional transportation modes.

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* Corresponding author. SDA Bocconi School of Management, Milan, Italy.
E-mail address: pietro.degiovanni@sdabocconi.it (P. De Giovanni).

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Although the advantages associated with the adoption of e-scooters are well-documented in the literature, there are also drawbacks related to the service. Improper behaviors exhibited by e-scooter users can have negative consequences for both cities and urban mobility systems. Behaviors like double-riding or not wearing helmets pose significant safety risks to both e-scooter users and pedestrians. Irresponsible parking of e-scooters in busy pedestrian areas obstructs pathways, hindering the movement of pedestrians and other vehicles, leading to bottlenecks, delays, and commuter frustration. Engaging in actions such as riding on sidewalks, weaving through pedestrian crowds, or disregarding traffic rules can also result in negative public perception, impacting the acceptance of e-scooters as sustainable transportation mode. This negative sentiment may lead to increased restrictions or even bans on e-scooter usage, limiting their contribution to an efficient urban mobility.

Furthermore, improper usage of e-scooters can have adverse effects on urban infrastructure, including sidewalks, pedestrian areas, and public spaces. Reckless riding and parking in prohibited zones can lead to the deterioration of infrastructure components, compromising the city's visual appeal and incurring higher maintenance costs. Repairing damaged infrastructure diverts valuable resources that could have been allocated to other critical urban development initiatives, hindering overall progress and growth. Gössling (2020) identifies three main types of irresponsible behaviors associated with e-scooter users in many cities: riding, cluttering, and vandalism. Irresponsible riding encompasses behaviors such as riding recklessly on sidewalks and pedestrian areas, violating restricted zones, exceeding speed limits, carrying multiple riders, not wearing helmets, riding under the influence, and disregarding crosswalk regulations. Cluttering involves problems like improper parking in restricted areas, obstructing public transportation infrastructure, impeding pedestrian pathways, and neglecting proper e-scooter parking. Finally, vandalism pertains to damages such as discarding e-scooters in bodies of water and common acts of destruction, including helmet theft.

Fig. 1 illustrates various improper behaviors associated with riding e-scooters in the city, which can lead to damage both to the city's urban infrastructure and the e-scooter service firm. In Fig. 1a, the usage of e-scooters by two people poses serious safety risks, overloading the engine, burning out the motor, and tripping the overload safety circuitry. Excessive weight, such as an extra person or luggage, strains the tires, increasing the risk of skidding. In Fig. 1b, riding e-scooters on sidewalks may cause injuries to pedestrians, particularly elder and disabled individuals, especially in narrow roads lacking bike lanes or with fast traffic. Fig. 1c depicts riders not wearing helmets, resulting in a high risk of fatalities. Additionally, Fig. 1d and e shows riders on crosswalks and e-scooters being left anywhere due to their dockless nature, respectively. While this convenience may seem appealing to users, irresponsible parking of e-scooters can be a nuisance. Fig. 1f, g, 1h, and 1i demonstrate riders disregarding public facilities when parking or abandoning e-scooters, leading to several issues. For instance, parking at emergency exits and doorways can block pathways and cause accidents, while parking at bus stops or subway stations obstructs pedestrians and other modes of transportation. Similarly, leaving e-scooters flat on the ground obstructs pedestrian paths and hinders other riders from accessing them (Fig. 1j). Fig. 1k shows a rider drinking alcohol while driving, a severely prohibited action. Such improper behaviors can have significant negative consequences for both urban infrastructure and e-scooter service providers.

The trade-offs observed in the real-life cases concerning e-scooters as smart mobility solutions for cities have been the inspiration behind this research. The study contributes to existing literature by introducing a game-theoretic model involving a city and an e-scooter service firm. Within this model, the city determines the optimal amount of urban

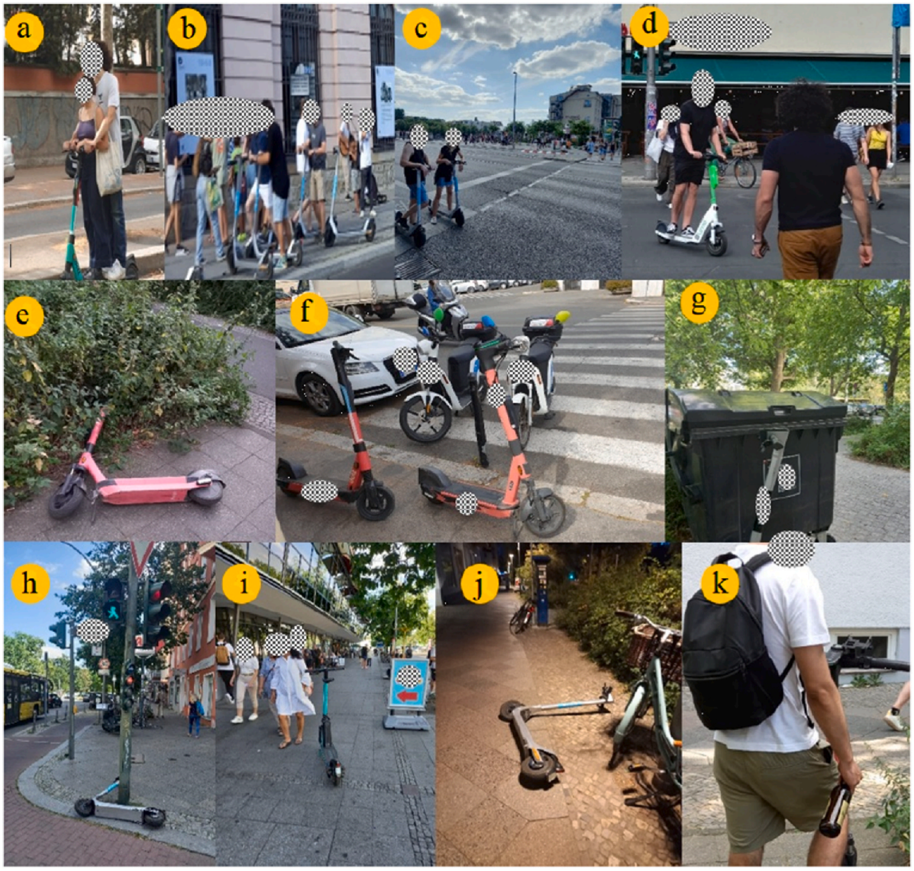

Fig. 1. Examples of users' improper behavior.

infrastructure necessary for ensuring efficient mobility throughout the territory. Simultaneously, the e-scooter service firm is responsible for determining the capacity of the e-scooter sharing system and setting the price for users. Our study focuses on analyzing the strategies employed by the city and the e-scooter service firm, particularly in relation to the demand for both traditional transport modes and e-scooters. We aim to evaluate the utility generated for the city and the profitability achieved by the e-scooter firm, providing insights into the effective management of e-scooter systems and investments in urban infrastructure. However, it is important to note that the game described above does not address the issues arising from the improper usage of e-scooters, which poses challenges for both involved players. For example, the city's infrastructure cannot be fully utilized or function optimally when e-scooter users disregard traffic signals and pedestrian areas. Similarly, the e-scooter service firm incurs costs when users fail to adhere to proper usage guidelines, such as overloading e-scooters with excessive luggage or carrying multiple passengers on a single scooter.

Among the array of solutions available to mitigate the improper use of e-scooters, blockchain technology emerges as a promising method to prevent such behaviors effectively. The mobility sector has already witnessed diverse applications of blockchain, including car wallets and payments, electric vehicle charging payments, platooning, smart insurance, keyless authentication, infrastructure sharing, mileage databases, and digital service records (Gosele and Sandner, 2019). In this study, we propose implementing blockchain as a powerful deterrent for reckless e-scooter usage by introducing a user registration system with valid identification. Users are made aware that their actions can be traced back to them, thus curbing the likelihood of improper behaviors. Smart contracts are activated to enforce appropriate penalties or warnings when users violate the established rules, and these contracts are informed by data collected from various sources within the city, namely, hardware oracles; the latter play a crucial role in this system, as they gather data from the physical environment and integrate it into the smart contracts (De Giovanni, 2022a). This data is sourced from diverse devices, including surveillance cameras, face recognition cameras, cameras installed on e-scooters or helmets to detect the environment, weight sensors, balance recognition sensors, speed sensors, GPS, videos and photos taken by pedestrians, and stoplight sensors.

Accordingly, we propose a second game theory model that incorporates the blockchain system, along with all the previously mentioned components. In this model, the e-scooter firm invests in blockchain technology to detect and deter improper behaviors while continuing to manage the e-scooter capacity system and set the service price. The presence of blockchain technology can have a dual effect on e-scooter demand: on one hand, it may increase demand as users perceive the blockchain's presence as a guarantee of a highly controlled and well-functioning transportation system, which prevents the adoption of proper users' behavior; on the other hand, some e-scooter users may opt to no longer access the service due to the systematic monitoring and control imposed by the blockchain and prefer using their own vehicles. Simultaneously, the two players engage in negotiations regarding a fee that can be charged in a dual way: to the city as a counterpart for enhancing the level of mobility service or to the e-scooter firm as a counterpart for accessing the city's physical oracles.

Our results demonstrate that the adoption of blockchain technology consistently shapes the strategies employed by e-scooter firms. However, its impact on the city's infrastructure investments is dependent on the activation of city objects as hardware oracles through the blockchain. This activation allows the city to enhance its urban infrastructure more effectively, particularly when the hardware oracles generate tokens or cryptocurrencies. Besides, e-scooter firms need to adapt their investments in service capacity based on users' willingness to embrace self-control and blockchain monitoring. Additionally, firms should proactively identify and penalize improper user behavior to improve the security of e-scooter services. The interplay of these factors ultimately determines the investments in blockchain technology. Moreover, users who exhibit responsible and proper behavior while using e-scooter services should be incentivized with lower service prices. Conversely, users who display hesitance towards blockchain monitoring may exhibit a propensity for dishonest and improper behaviors. To discourage such behaviors, e-scooter firms have the option to increase service prices. Consequently, the adoption of blockchain technology has the potential to drive increased demand for e-scooter services. By detecting and addressing improper usage behaviors, these systems become more efficient, safer, and reliable, leading to a positive impact on the overall e-scooter experience.

The paper is organized as follows. Section 2 presents the literature on mobility games and blockchain, highlighting the research gap. Section 3 introduces the games, which are subsequently solved in section 4. In section 5, a comparative analysis of the equilibria and findings is presented analytically, while section 6 conducts a numerical analysis to compare profits and utilities in both games. Section 7 lists the managerial insights and implications. Section 8 briefly concludes and identifies potential avenues for future research.

2. Literature review

While there has been significant empirical and qualitative research on smart mobility (see, for instance, Zhang et al., 2021; Ahadi et al., 2023), the literature on game theory applied to smart mobility is relatively new. The regulation of smart mobility has only emerged in the last decade, and game theory research in this field has started to develop more recently. Some articles concentrate on the policies and government role in improving smart mobility systems. For example, to explore the dynamics of cooperation and competition between urban public bicycles and shared bicycles in Xi'an City, Liu et al. (2018) employ game theory to analyze the costs associated with shared mobility. They propose a three-player game involving the shared bicycle operator, the public city bicycle operator, and the government. The study reveals that there are incentives for bicycle enterprises to collaborate in the implementation and management of their systems, resulting in reduced costs, particularly when the government is actively involved. In a similar vein, Wang et al. (2020) apply a three-player evolutionary game theory to the context of China's Internet ride-hailing framework. Their study considers the government, the online vehicle platform security monitoring department, and car-sharing owners as the players in the game. By examining this dynamic, they shed light on the interplay between the stakeholders and the strategies they adopt.

Additionally, Sun et al. (2019) conduct a comprehensive study utilizing a two-dimensional game model involving the government and ride-hailing platforms. The research examines the stability strategies adopted by both participants in different scenarios. In their model, the government can adopt two regulatory strategies: "strict regulation" and "loose regulation." Similarly, the ride-hailing platforms are considered to have two strategic options: "scale expansion" and "service promotion." The study provides solutions for the tradeoffs between the government and the ride-hailing platforms, considering the implications of various strategies. Furthermore, other articles also delve into game theoretical models for smart mobility, particularly concerning pricing and profit considerations. Zardini et al. (2021) introduce a comprehensive modular game-theoretic framework that encompasses various types of mobility service providers, municipal actions, and customer choice models within the shared mobility system. Their study delves into the intricate interactions among stakeholders within the mobility ecosystem while addressing operational considerations for mobility service providers, including pricing strategies, fleet size determination, and vehicle design. By developing a game theory-based pricing method for ridesharing, Magsino et al. (2023) evaluate the problem of passenger pairings, which causes an overlapped and shared travel distance between two commuters. The devised model aims to reduce travel costs while keeping the driver's revenue approximately equal. Their analysis of urban mobility demonstrates how to reduce the taxi trips for people and lower the passenger fare rate (cost per kilometer); however, there would be a slight increment in their travel distance.

In the literature, numerous articles employ game theory models to enhance the operational performance of smart mobility systems. Amar and Basir (2018) present a game-theoretic model focusing on social taxi networks and formulating the territory sharing problem. The challenge arises from the tendency of most social taxi drivers to concentrate in areas with the highest anticipated number of customers, which can negatively impact business profits due to an oversupply of services. To address this, they propose a no-regret model implemented through a smart app, leading to an outcome corresponding to a coarse correlated equilibrium. This approach enables drivers to engage in a cooperative endeavor, earning the right to operate in specific attraction areas. With the intend to provide an analysis of combined smart mobility, Zhou et al. (2023) develop a game with one player being the metro and another player being the bike, which compete and integrate at the same time to improve the mobility. The players can use a cost-sharing mechanism as well as an information sharing mechanism to coordinate their strategies, maximize the utility, and increase the demand for smart mobility. Similarly, Emami et al. (2022) develop a game-theoretic approach to assess the dynamics of urban modal competition, specifically the competition between public transportation and private cars, along a corridor connecting a city center to a suburban neighborhood. Their results demonstrate that enhancing transit access time through integration with a bike-sharing system increases the total demand for public transportation. Bui and Jung (2018) and Khan et al. (2023) discuss using game theory models to manage traffic loads and reduce intersection traffic intensity and average waiting time. By employing game-theoretic principles, these studies propose traffic management strategies that optimize traffic flow, alleviate congestion, and enhance overall mobility within smart cities.

Overall, the application of game theory models in the context of smart mobility showcases the versatility and potential of this approach in addressing various challenges and improving the efficiency and effectiveness of urban transportation systems. However, we have identified a research gap that encompasses several critical aspects that have been overlooked in previous studies, consisting of four specific points: 1) Existing game theory research fails to address the intricate relationships between a city and an e-scooter company within the realm of smart mobility systems. By examining these interfaces, we aim to shed light on the strategies and decision-making processes that can optimize outcomes for both parties involved; 2) No research takes into account the coexistence of traditional mobility systems alongside the emerging smart mobility systems. We recognize the interplay between these two frameworks, wherein smart mobility acts as a valuable complement to traditional transport modes. We have jointly modeled them in a game-theoretical model to provide a more comprehensive understanding; 3) So far, game theory research has not modeled the city's infrastructure as a strategic variable. The city's infrastructure not only serves as a crucial sponsor for e-scooter systems but also enables the effective management and maintenance of e-scooter services; 4) No research in game theory has modeled the impact of e-scooter users' behaviors on the overall success of smart mobility. When utilized properly, smart mobility systems bring substantial benefits to all stakeholders involved. However, improper e-scooter usage poses a detrimental threat to the efficiency and viability of smart mobility. By exploring user behavior patterns and promoting responsible usage, we aim to unlock the full potential of smart mobility for the benefit of cities, e-scooter companies, and users alike.

Furthermore, our research seeks to highlight the importance of proper behaviors by e-scooter users. In fact, their increasing use, which has surpassed the utility of public bicycle-sharing systems and shared e-scooter firms, will control the micromobility market, resulting in various serious issues that tend to overcome their positive impacts. The main inappropriate behaviors of e-scooter riders include riding at high speeds, using sidewalks or pedestrian areas, parking in prohibited areas, riding without wearing helmets, double riding, and vandalism (De Bortoli and Christoforou, 2020). To address these issues, cities are developing guidelines and policies that could reduce these problems through establishing proper frameworks for e-scooter operations. These frameworks include defining acceptable operating speeds, helmet requirements, minimum age for use, permitted operation locations, and organized parking areas despite their dock-less nature (Gössling, 2020). However, it seems that the majority of local authorities have not yet prepared the necessary regulations for efficiently integrating e-scooters into the urban context (Chang et al., 2019).

The traditional mechanisms often fail to decrease the number of improper behaviors due to a combination of factors. Inadequate resources, limited enforcement personnel, and the sheer scale of monitoring large numbers of e-scooter riders make it challenging to address every instance of improper behavior effectively. Additionally, a lack of awareness, education, and clear communication about rules and consequences can contribute to non-compliance. To overcome these limitations, cities are increasingly exploring innovative solutions, such as leveraging technology, implementing stricter regulations, and integrating advanced monitoring systems. Among the various digital solutions available for cities, recent literature has demonstrated the effectiveness of blockchain technology for addressing security, collaboration, and traceability issues in smart mobility systems. Numerous case studies and real-world applications have demonstrated the benefits of blockchain technology across diverse industries (e.g., Pu and Lam, 2023; Calandra et al., 2023; De Giovanni, 2022a). Notably, the application of blockchain has extended into the realm of smart cities, where it has shown promise in various research. For instance, Lopez and Farooq (2020) propose a multi-layered blockchain framework for the Smart Mobility Data-market (BSMD), wherein participants, including federal, provincial, and city governments, universities, ride-hailing companies, and non-profit transportation organizations, share encrypted data with the blockchain network and with each other. They emphasize data ownership, transparency, auditability, and access control as core principles of the BSMD. In contrast, Kim et al. (2021) utilize blockchain technology in a decentralized car-sharing service to ensure data integrity. They analyze the computation and communication costs of the proposed car-sharing system, which can be secured against various attacks and provide mutual authentication using informal analysis, automated validation of Internet security protocols, applications simulation, and logic analysis. In the context of shared mobility, Auer et al. (2022) study blockchain and IoT technologies to advance car-sharing through a conceptual design and architecture of a blockchain-IoT-based car-sharing platform. They develop a prototype for keyless vehicle access control to analyze car-sharing and leasing processes, finding that blockchain technology facilitates collaboration and reduces the need for trust to some extent. For bicycle sharing systems, Zhao et al. (2020) investigate the use of blockchain technology to reform the current management mode for shared bicycle deposits. They develop a decentralized, user-information and deposit-visualized, multidimensional supervised management system to implement real-time flow direction supervision of user deposits.

Through our analysis of the blockchain-related literature review, it becomes evident that cities and other stakeholders are keenly interested in leveraging blockchain to enhance smart mobility. However, we have identified a second gap in the literature pertaining to the use of blockchain by cities and e-scooter companies to address issues arising from the improper use of e-scooters. To fill this gap, our aim is to contribute to the existing literature by proposing a second game model for smart mobility that incorporates blockchain technology. This model aims to detect inappropriate behaviors while considering its dual effect on both demand and profit function.

Blockchain technology, along with its associated smart contracts, holds promise as an efficient solution for detecting and penalizing improper behaviors of e-scooter users. Its alignment with the highlighted issues can be outlined as follows.

1. Blockchain offers a decentralized and immutable ledger, ensuring transparent and tamper-proof recording of all transactions and data (Helo and Hao, 2019). This capability allows for the creation of a comprehensive and reliable record of e-scooter usage, including information related to improper behaviors. Furthermore, all relevant stakeholders, including city authorities, e-scooter companies, and users, can access the same transparent information, fostering trust and accountability.
2. Integration of smart contracts into the blockchain enables the encoding of specific rules and conditions, ensuring automatic enforcement and penalties for improper behaviors (De Giovanni, 2020). For example, if a user is found riding without a helmet or exceeding speed limits, the smart contract can automatically trigger penalties, such as fines or temporary suspension of the e-scooter service. This automation eliminates the need for manual intervention and enhances the efficiency and consistency of enforcement. Additionally, the blockchain records the improper behaviors, providing unquestionable and uncontestable evidence for the activation of smart contract penalties.
3. Blockchain can seamlessly integrate with hardware oracles, such as surveillance cameras, sensors, or GPS devices, to collect real-time data on e-scooter usage and user behaviors (De Giovanni, 2022b). These data sources feed information directly into the blockchain, enabling immediate detection of improper behaviors. The decentralized nature of blockchain facilitates the collection of data from multiple sources, offering a comprehensive view of the e-scooter ecosystem.
4. Blockchain ensures proper user identification by linking digital identities (Yang and Li, 2020) to the e-scooter system. Through registration and verification processes, users are assigned unique digital identities stored on the blockchain. This prevents anonymous or fraudulent usage of e-scooters and holds users accountable for their actions.

To the best of our knowledge, no article has investigated the adoption of blockchain for alleviating the improper behavior of e-scooter users in a game theoretical model between the city and the e-scooter company. Thus, we seek to compare related strategies, demand, and players' payoffs with the results of the game without blockchain, to highlight the benefits that the technology provides and recommend the most suitable implementation path within the context of smart cities. Table 1 displays the comparison between shared bikes and e-scooter smart mobility systems, to position the contribution of our research. The comparison presented in Table 1 shows some similarities between the operations and maintenance of shared bikes and e-scooters, therefore suggesting that the model proposed in this paper can be extended to shared bike systems, on which the literature has developed extensively in the last decade. In fact, the two shared mobility systems both depend on urban infrastructure, usage-based pricing strategies, and regular maintenance to guarantee the availability of fleets and their safety, while inappropriate usage and vandalism of devices pose important operational concerns.

Despite these similarities, several differences still exist between the two smart mobility solutions. The sensitivity of e-scooters to infrastructural support, such as charging stations and special parking zones, is much more pronounced than shared bikes options, which rely instead on a mechanical system. Yet, shared bikes do not need any charging infrastructure but greatly rely on periodic mechanical maintenance, such as chain or tire replacements. Instead, the e-scooters are more tied to the IoT technology and digital application for fleet management, posing additional challenges in the monitoring and control of their usage compared to shared bikes. The e-scooter system requires attention on aspects like battery charging infrastructure, more advanced integrations of IoT, and dynamic pricing to consider demand patterns. Therefore, the model that we propose in this research can be easily extended and applied to other smart mobility solutions but different operating and

Table 1
Comparison between shared bikes and e-scooter systems.

Feature/Model	Shared Bikes (Literature Review)	E-Scooters (Proposed Model)
Regulatory Focus	Shared bike systems typically involve a regulatory framework in which the government collaborates with bike operators and public transport systems (Liu et al., 2018).	E-scooter systems also require close interaction between city authorities and operators. However, the focus in our model is on how these relationships influence user behavior, leveraging blockchain to enforce regulations and manage real-time penalties.
Key Players in Game Theory	Game theory models for shared bikes typically involve government, bike operators, and public transportation systems (Liu et al., 2018; Zhou et al., 2023).	In our e-scooter model, the main players are the city, e-scooter companies, and users. The inclusion of user behavior as a strategic variable differentiates this model, where blockchain technology plays a critical role in influencing these dynamics.
Mode of Transport	Shared bikes are non-motorized and have minimal technical requirements compared to e-scooters, resulting simpler in terms of maintenance and operation, without the need for battery management (Zhou et al., 2023).	E-scooters, being motorized, require more complex operational management, particularly related to battery charging and maintenance. This adds additional layers of complexity in the model, particularly in terms of how blockchain can optimize operational aspects.
User Behavior	User behavior in shared bike systems tends to be more predictable and less risky, with fewer safety concerns related to speed or improper usage (Liu et al., 2018).	In contrast, e-scooter systems face more pronounced issues with user behavior, such as speeding and illegal parking. Our model emphasizes the use of blockchain to monitor and enforce penalties for improper behavior, aiming to improve system efficiency and safety.
Infrastructure's Role	The role of infrastructure in shared bike is less critical compared to e-scooters. While infrastructure such as bike lanes can enhance usability, shared bikes can function across a variety of urban environments (Emami et al., 2022).	E-scooter systems are more dependent on dedicated infrastructure, such as specific lanes and designated parking areas. The availability and quality of infrastructure directly affect user adoption and operational success, making it a strategic variable in our model.
Blockchain's Role	In shared bike systems, blockchain has been explored for specific use cases, such as deposit management and financial transparency (Zhao et al., 2020)	In e-scooter systems, blockchain plays a more comprehensive role by tracking user behavior, managing smart contracts, and automating penalties. This ensures transparency, reduces enforcement costs, and improves compliance in real time, which is critical to system success.
Game-Theory Focus	Game theory models for shared bike systems often focus on optimizing operational performance, cost-sharing mechanisms, and collaboration between stakeholders (Liu et al., 2018; Zhou et al., 2023).	Our e-scooter model incorporates game theory to address strategic interactions between cities and e-scooter companies, with user behavior being a critical component. Blockchain enhances these interactions by ensuring that compliance and enforcement are integrated into the model.

(continued on next page)

Table 1 (*continued*)

Feature/Model	Shared Bikes (Literature Review)	E-Scooters (Proposed Model)
Policy Implications	In shared bike systems, policy recommendations tend to focus on improving collaboration between public and private operators (Liu et al., 2018; Emami et al., 2022).	For e-scooters, policy recommendations emphasize the regulation of user behavior through penalties, which are automated via blockchain. This approach ensures that improper usage is swiftly addressed, improving overall system efficiency and safety.
Model Complexity	Shared bike models often involve fewer dynamic variables, focusing on cost efficiency and operational performance. The systems are generally simpler to manage (Zhou et al., 2023; Liu et al., 2018).	The e-scooter model is more complex, involving multiple dynamic variables such as infrastructure, user behavior, and blockchain technology. The integration of these variables creates a more intricate system that requires advanced tools like blockchain to manage effectively.

financial dynamics necessitate significant adaptation.

3. Smart mobility models and games

3.1. A model of smart mobility without blockchain ($\mathscr{M}$ game)

We consider a game between a city, player G, and a firm providing e-scooter mobility services, player E. Table 2 lists the notations used for describing the course of the game. Since this is a game of smart mobility we refer to it as $\mathscr{M}$-game. G invests in mobility and infrastructure, I, to guarantee urban mobility. According to The World Bank (2016), the latter consists of "moving people from one location to another location within or between urban areas." Therefore, examples of urban mobility investments are paths, bridges, tunnels, and roads, as well as parking areas, surveillance and security cameras, and road signs and guidelines. Moreover, to move toward a smart city, investments in sustainable solutions - such as a cycling network to boost active travel (e.g., walking and cycling), connectivity for smart management, smart mobility vehicles, smart traffic management, and smart regulations - are strictly needed. Furthermore, smart cities are interested in implementing multimodal journey planning that considers secondary transportation modes like e-scooters to improve the efficiency of the main public transportation network (Baum et al., 2023). To make the urban mobility smart, player G can access the smart mobility services of player E, who is specialized in e-scooter services. E has a certain e-scooter fleet capacity to satisfy the demand for e-scooters. One key ingredient to attract consumers through the use of e-scooters is to provide high levels of services. In fact, E invests in service operations efforts, A, in terms of maintenance operations, platforms for managing and optimizing the e-scooter network, apps and internet applications to guarantee the correct booking service for users, and the hiring personnel to organize and guarantee the sharing system over the city. We assume that the capacity of e-scooters is E's property, which is shared according to circular economy principles and strategies of sharing outputs and is made accessible to users through investments in service operations, A, and at a price, p.

Table 2
Notations.

Notation	Description
G, E	Players of the game: Government, G, and e-scooter service firm, E.
α	Market potential of users interested in e-scooters
β	Sensitivity of users to e-scooter price service
δ	Sensitivity of users to service operations efforts
k	Sensitivity of e-scooter demand to urban infrastructure
c_F	Collection and maintenance cost parameter for E
d	Efficiency of urban infrastructure in reducing E's operational cost
θ	Fraction of users who engage in improper e-scooter behaviors
c	Marginal cost of improper user behavior for E
t	Marginal tax fee paid by E to G
D_E, D_G	Demands for e-scooter services and infrastructure, respectively
u_E, u_G	Marginal utility gained by E and G, respectively
γ	Fraction of users adopting proper behavior due to blockchain
B	Investment in blockchain technology by E
I	Investment in urban mobility and infrastructure by G
A	Investment in service operations by E
p	Price charged by E to users for e-scooter services
f	Fixed access fee paid by E to G for using hardware oracles
h	Fraction of urban infrastructure covered by hardware oracles
η	Sensitivity of users's reluctance to blockchain technology
Π_G, Π_E	Profits for G and E, respectively

The investments of both urban infrastructure and e-scooter capacity take quadratic and convex forms and are given as follows: $C_I(I) = \frac{c_I I^2}{2}$ and $C_A(A) = \frac{c_A A^2}{2}$, with $c_I > 0$ and $c_A > 0$ being positive and constant parameters that explain the investments efficiency and measure their impact on the players' objective functions. The use of convex and quadratic forms for such types of investments is widely employed in game theory applications to indicate a player's efforts in a certain policy or strategy, such as, advertising, promotion, the circular economy, blockchain, and smart technologies.

In this work, quadratic and convex cost functions is a strategic choice from the mathematical bases of game theory as well as practical realities of economic and strategic decisions in smart mobility and infrastructure development. Strategies in the game-theoretic analysis must be modeled to ensure a well-defined stable equilibrium. The application of quadratic cost functions concerning the investments naturally ensures this because such cost functions are concave concerning the objective function and, consequently, they ensure that the second-order conditions for a maximum. Specifically, the first derivative of a quadratic function-a linear term-represents the marginal cost of increasing the investment, which, for initially small investments, increases the payoff. The second derivative, being a constant term, represents the increase in marginal costs, that is, the notion fully in line with economic principles that beyond a certain threshold, additional investments yield smaller returns. This relationship ensures that the payoff function reaches its maximum value at some finite level of investment-a circumstance under which investment behaviours conform to more realistic economic scenarios in which unlimited spending is neither practical nor beneficial.

From the perspective of practical implications and economic rationale, the quadratic and convex investment functions also mirror how real-world economic phenomena in investment have high returns up to a point after which the returns diminish. A good case in point is that of infrastructure such as roads or digital technologies, whereby early investments greatly improve efficiency of service or user satisfaction. However, the marginal benefits fall because further investment from saturation effects is continuously increasing; infrastructure might get overbuilt or technology too sophisticated for practical needs, thus not proportionally increasing the utility or profits (see Rust et al. (2006) for an example). Besides, convexity in the cost function is a quite realistic model of the economic principle of growing opportunity costs. This is evident in cases involving urban mobility and smart technologies, where the more capital invested in pioneering infrastructure or advanced systems, the greater will be the cost diverted from other critical areas such as basic services or maintenance. This models the real-world trade-offs faced by urban planners and companies alike: while investments are certainly necessary for growth and efficiency, they do have to be strategically balanced in a manner that would optimize overall system performance without leading to resource misallocation.

One can indeed model the investments using a linear cost function where the cost or benefit associated with each unit of investment remains the same regardless of scale. This absence of curvature in the investment function-that is, constant marginal returns-implies that the strategy will not be concave with respect to the objective function. In game theory, as well as in optimization, an absence of concavity could cause multiple or unstable equilibria, or even to equilibria not to exist. This complicates strategic decisions in fields concerned with economic variability and the model feasibility. To represent this in a linear model, one would have to include quadratic relationships in other parts of the model-say, in the demand functions of smart mobility. For example, the effect of increased investments may have to be modeled to show its diminishing returns within the demand function itself. This would make the model cumbersome and probably obscure the direct influence of investment in the outcome. Also, the linear model of investment presumes that each additional units of expenditure add to return, which could only be unrealistic scenarios of unlimited or unbounded investment without consideration of diminishing operational benefits. In fact, most economic and business scenarios are dominated by the occurrence of returns to scale whereby beyond certain thresholds, the returns on investments would yield progressively lower benefits and may even incur greater costs or inefficiencies.

The investments in both urban infrastructure and e-scooter service operations, along with the price, represent the players' strategies and contribute to their wellbeing. E is a firm that seeks to maximixe her business opportunities and that considers the market for e-scooter services when making her decisions. Such a market is given by $D_E(A,p,I) = \alpha - \beta p + \delta A + kI,$ where α and β are two positive parameters that are essential for understanding the e-scooter market. α represents the market potential and is determined by the number of users who are attracted to the e-scooter service. Furthemore, β measures the users' sensitivity to price and represents the number of users who abandon the e-scooter service because of the price. In other words, it measures the amount of users that E loses for any marginal increase in price. There are various sources available that indicate that e-scooter access increases as the price decreases. There is uniform evidence from studies showing that demand decreases linearly with increased prices of the service. For instance, Li et al. (2021) explored shared mobility systems and established that through pricing strategies, demand could be reduced efficaciously in a highly predictable way. This is particularly true for e-scooter services, where the demanders are very sensitive to prices. Furthermore, the parameter δ represents the users' sensitivity to other factors such as availability, functionality, and maintenance of the e-scooter service. Research on shared mobility, such as those by Ciari et al. (2015), have underlined that increasing service quality and operational efficiency-in terms of maintenance, development of apps, and optimization of the network-determines user demand in a positive and linear way. This applies to e-scooter services whereby the better an infrastructure is serviceable and maintained, the greater will be its use.

Finally, the parameter k represents the users' sensitivity to the urban infrastructure. This parameter informs on the relationship between the investments in urban infrastructure and the access to e-scooter services, whose linearity has been empirically proved by Castiglione et al. (2022). Specifically, they show that increasing levels of perceived infrastructural safety due to properly designed urban infrastructure linearly increase demands for shared mobility solutions, including e-scooters. Regarding this relationship, two scenarios are possible: 1. Urban infrastructure can positively contribute to the increase in demand for e-scooters. 2. Urban infrastructure may have either an insignificant or negative influence on e-scooter demand. In the former case, investments in urban mobility improve accessibility to e-scooters, leading to higher utilization and availability for commuters and residents. For instance, road design, bike lanes, roadways, and sidewalks can positively impact consumers' willingness to rent e-scooters (Yang et al., 2022). In the latter case, investments in urban infrastructure do not result in a higher demand for e-scooters. Empirical evidence from Zhang et al. (2021) shows that e-scooter users are unaffected by certain urban infrastructures such as pedestrian-exclusive ways, primary roads, service roads, tunnels, and bridges. However, they are deterred by urban features like stairs, left-turn and U-turn intersections, and turns without intersections. These findings align with the results of Zuniga-Garcia et al. (2021), who report that 38% of e-scooter users travel distances without utilizing conventional urban infrastructure such as sidewalks, bike lanes, and roadways. Considering the contrasting effects of urban infrastructure on e-scooter demand, a specific section (Online Appendix C, D, and E) will analyze its impact.

We assume that each user accessing the e-scooter service originates a marginal revenue given by $\pi_E = p - c_F(1 - dI) - c\theta,$ with $c_F,$ $d,$ c and θ being constant and positive parameters. c_F represents the collection and maintenance costs that E faces. When the urban infrastructure is well organized to accommodate and manage services like e-scooters, the e-scooter network can be better managed. For example, dedicated infrastructure for e-scooters, such as bike lanes or separate lanes for micromobility vehicle, would help separate e-scooter riders from other forms of traffic and make it safer for riders. Furthermore, providing designated parking spaces for e-scooters can help prevent cluttering of sidewalks and ensure that e-scooters are not obstructing pedestrian walkways or causing safety hazards. Nowadays, cities can support the smart mobility by installing charging stations for e-scooters at strategic locations: This would help to ensure that e-scooters are charged and ready for use, reducing the chances of riders leaving them in inconvenient locations. Therefore, for any investments that G makes in infrastructure, E's collection, logistics, and maintenance costs decrease through the parameter d. Finally, the literature reveals that the major problem e-scooter firms face consists of the improper use of e-scooters by users such as damaging the scooters by leaving them lying on the ground or any other improper parking behavior, riding e-scooters by more than one person, blocking public places or obstructing public facilities, putting pedestrians in danger by driving e-scooters on sidewalks and crosswalks, riding e-scooters at high speed on downhills, and not wearing helmets. We capture this effect by $\theta,$ which is the fraction of users undertaking improper behaviors and incorrectly using the e-scooters. These unconventional behaviors generate a marginal cost for improper usage behaviors, $c,$ because of damaging e-scooters via double riding, leaving e-scooters lying flat on the ground, and incurring accidents. Moreover, this improper behavior may damage the company's brand and this can be considered in the proposed marginal cost. Furthermore, we introduce the tax parameter $t > 0$, which represents the marginal fee that the e-scooter service firm transfers to the city based on the user-generated revenue. This tax reflects the financial contribution of the company to the city's infrastructure or regulatory oversight, ensuring that the firm bears part of the costs associated with maintaining urban mobility systems, such as setting up docking spaces, dedicated lanes, or managing the environmental impact of e-scooter usage. The tax can also serve as an incentive for companies to improve compliance and operational efficiency, aligning with the city's regulatory objectives.

Unlike E, G is a player belonging to the public domain and seeks to increase accessibility to the infrastructure for society. Hence, urban mobility is described by $D_G(I,A,p) = gI - \theta D_E(A,p),$ with g being a positive constant that explains the society's urban mobility realized through G's investments in urban infrastructure. Interestingly, the urban mobility $D_G(I,A,p)$ is negatively influenced by the demand for e-scooter, $D_E(A,p),$ given the negative externalities cities are facing due to the improper use of e-scooters, as exemplified by $\theta.$ In fact, improper behavior in riding or parking e-scooters causes difficulties in using sidewalks and public transportation facility station. Moreover, riding e-scooters without helmets, riding them at high speed, and riding them on sidewalks and crosswalks brings to mind that e-scooters can be dangerous for riders as well as pedestrians, which results in a decrease in the current and potential users of scooters and e-scooters or other similar transportation modes such as bikes, in the city. Therefore, traditional users' mobility can be harmed by the presence of e-scooters in the urban space. Urban mobility, $D_G(I,A,p),$ and smart mobility, $D_E(A,p),$ generate benefits u_G and $u_E,$ respectively, and represent the marginal utility that is gained by guaranteeing mobility. This assumption is in line with Wang et al. (2023), according to whom the smart mobility complements the urban mobility instead of replacing it completely. Providing the proper infrastructures leads to increases in urban mobility, reductions in congestion, time savings for citizens, new job opportunities, and enhanced emissions reductions, which can be considered as $u_G > 0$. At the same time, e-scooters can assume a very positive role in connecting different public transportation systems, such as bus stations and trains, which in turn leads to an increase in using the infrastructures provided instead of personal vehicles. This aspect is captured through $u_E > 0$. Therefore, although $D_G(I,A,p)$ decreases in $D_E(A,p)$, the presence of e-scooter services ensures smart access to mobility through the sharing platforms. The simultaneous presence of u_G and u_E and the trade-off induced by $D_E(A,p)$ render the players' decisions very challenging.

Finally, the $\mathscr{M}$-game takes the following structure: $U_G^{\mathscr{M}} = \max_{I\geq 0}\left\{u_G\{gI-\theta[\alpha-\beta p+\delta A]\}+(u_E+t)[\alpha-\beta p+\delta A]-c_I\frac{I^2}{2}\right\}$ and $\Pi_E^{\mathscr{M}} = \max_{A\geq 0,p\geq 0}\left\{[\alpha-\beta p+\delta A](p-t-c_F(1-dI)-c\theta)-c_A\frac{A^2}{2}\right\}$. Note that we use $U_G^{\mathscr{M}}$ to refer to the utility that G seeks to optimize, while we refer to $\Pi_E^{\mathscr{M}}$ to indicate the profits that E seeks to maximize. In fact, G maximizes the utility generated by ensuring that people can mobilize around a city and easily gain access to all services and facilities. In contrast, E provides e-scooter services to maximize her payoff function.

3.2. *A model of smart mobility with blockchain ($\mathscr{B}$-game)*

The $\mathscr{M}$-game leaves an important smart city issue to be solved. That is, how can the percentage of improper e-scooter usage, θ, be removed? In fact, θ creates important operational challenges for E and harms the security around the city for G. Among the various digital technologies available to detect users' improper e-scooters usages and behaviors, recent applications of blockchain technology integrated within hardware oracles represent a valid and suitable option. The blockchain's integrates physical systems to detect behaviors and activate the smart contracts accordingly. Therefore, in this paper, we explore the application of blockchain functionalities in smart mobility systems, particularly focusing on the utilization of hardware oracles. Hardware oracles are specifically designed to collect information from the physical world and relay it to the blockchain and smart contracts. Various types of information-reading devices can serve as hardware oracles, including surveillance cameras, face recognition cameras, weight measuring sensors, stoplight sensors, electronic sensors, barcode/QR scanners, RFID tags, laser sensors, IoT devices, robots, and other similar devices. For instance, surveillance cameras can be employed to monitor and verify riding behavior on crosswalks, while face recognition cameras can be utilized to ensure helmet usage and verify the identity of the e-scooter rider. Laser sensors can play a role in enforcing proper parking behavior, and weight sensors can prevent double riding incidents. In this study, our primary objective is to analyze the potential of incorporating physical urban mobility systems, such as cameras, as hardware oracles. Comparatively to previous studies, the role of blockchain is analyzed by considering the potential in mitigating improper e-scooter usages. For example, cameras are commonly used to verify vehicle speeds, ensure adherence to traffic lights, and monitor access to restricted zones within the city. The information to be collected from the ecosystem links to the improper behavior of users, which can be recorded in the blockchain, allowing the smart contract to compute a fee, γB, to compensate for the cost of unethical and dishonest behaviors, which are exemplified by not using the e-scooters properly. The second novelty for evaluating blockchain is represented by the activation of a payment linked to the infrastructure access and use. Since the hardware oracles are city property, the e-scooter company pays a fixed access fee, $f > 0$, while the total amount of the service depends on the infrastructure supported by hardware oracles, given by hI, with $h \in [0,1]$; the latter represents the fraction of infrastructure covered by hardware oracles. However, it is also plausible that $f < 0$, indicating that the city provides incentives to the e-scooter service firm for implementing a blockchain system capable of converting physical objects into hardware oracles and utilizing them to activate smart contracts. This incentivization could motivate the city to enhance the level of security and safety on the roads. Finally, the third novelty of our model linked to blockchain regards the introduction of the term ηB, to measure the effect of blockchain investments on e-scooter demand, which takes the form $D_E^{\mathscr{B}} = \alpha - \beta p + \delta A - \eta B$. On the one hand, some users may feel uncomfortable with the amount of surveillance and data gathering related to blockchain monitoring systems. For instance, some may resist or avoid using a service if it requires the collection of sensitive personal data, such as face recognition or location tracking, due to ethical or privacy-related concerns. In this case, the demand function considers the term $\eta > 0$ indicating the users' reluctance in blockchain, showing the amount of users not accessing to the e-scooter services because the blockchain entails unwanted effects. On the other hand, the blockchain can be perceived as a driver for enhacing the adoption of e-scooters if it is linked with enhanced safety, reliability, and transparency for users. For example, hardware oracles as cameras can provide face recognition and parking sensors guarantee conformation to the regulations of safe driving-wearing helmets, proper parking and build the confidence of service users. In this case, the demand increases with the investments in blockchain, resulting in users not being reluctant in having the blockchain inside the e-scooter service and, consequently, $\eta < 0$. In sum, the three terms γB, hI, and ηB represent new blockchain attributes and novel interactions that blockchain entails, whose investigation makes this research different from the literature.

According to Biswas et al. (2022), blockchain provides the capability to monitor improper behavior in real-time and reduce it, hence enhancing the service experience overall. In this way, it diminishes negative externalities, which, in turn, increases user confidence and raises demand. This can be modeled by a linear function between investments in blockchain and demand for e-scooters.

To capture the effect of blockchain on behavior, we assume that E invests in a certain blockchain technology to mitigate the effect of the fraction θ e-scooter users. According to Biswas et al. (2022), the investments in blockchain technology take the form $C_B(B) = \frac{c_B B^2}{2}$, where $c_B > 0$ is the efficiency parameter that informs the impact of blockchain investments in the E's objective function. Therefore, the $\mathscr{B}$-game takes the following form:

$U_G^{\mathscr{B}} = \max_I\left\{u_G(gI-(\theta-\gamma B)[\alpha-\beta p+\delta A-\eta B])+(u_E+t)[\alpha-\beta p+\delta A-\eta B] - c_I\frac{I^2}{2}+fhI\right\}$ and $\Pi_E^{\mathscr{B}} = \max_{A,p,B}\left\{[\alpha - \beta p + \delta A - \eta B](p - t - c_F(1 - dI) - c(\theta - \gamma B)) - c_A\frac{A^2}{2} - c_B\frac{B^2}{2} - fhI\right\}$.

4. Equilibria for the mobility games

4.1. *Equilibria of the smart mobility game without blockchain ($\mathscr{M}$-game)*

In the $\mathscr{M}$-game, G and E play the game à la Nash. Therefore, G sets the optimal infrastructure investments, $I^{\mathscr{M}}$, and E sets both the optimal price and e-scooter services, given by $p^{\mathscr{M}}$ and $A^{\mathscr{M}}$, respectively. Below we report the equilibria for the $\mathscr{M}$-game when $k = 0$ and $t = 0$, to keep the model tractable while analyzing both parameters afterwards.

Proposition 1. *Assuming an interior solution, the players' strategies in the $\mathscr{M}$-game are given by* $I^{\mathscr{M}*} = \frac{gu_G}{c_I}$, $A^{\mathscr{M}*} = \frac{\delta[c_F dgu_G\beta + c_I(\alpha-\beta(c_F+c\theta))]}{c_I(2c_A\beta-\delta^2)}$ *and* $p^{\mathscr{M}*} = \frac{(\delta^2+c_A\beta)(c_F dgu_G - c_I(c_F+c\theta)) - c_I c_A\alpha}{c_I(2c_A\beta-\delta^2)}$.

Proof. *See the Online* Appendix A. □

From the analysis of the optimal strategies displayed in Proposition

1, the strategic relationships between the two players emerge. Interestingly, G sets the optimal investments in infrastructure independent of E's decisions as $I^{\mathscr{M}*}$ is independent of the parameters of E's strategies. In fact, one can easily derive that $I^{\mathscr{M}*}$ increases the people's capacity to use the infrastructure, g, and G's marginal utility, u_G, while it decreases according to the infrastructure's efficiency, c_I. Therefore, when G sets infrastructure, he fully disregards the impact and the efficiency of E's strategies. In other words, a smart city engineers the whole project behind the city and estimates the utility for society, independent of the presence and the action of e-scooter firms.

In contrast, E's strategies are influenced by G's strategy and related parameters, as well as her own parameters. The term $c_F d g u_G \beta$ can be interpreted as the estimation of the benefits associated with the e-scooters, taking into account the logistics impact and G's marginal utility and benefits. However, it is crucial to balance these benefits with the consumers' willingness to access such a service, which is necessary to compensate for potential infrastructure inefficiency. Furthermore, the feasibility of optimal investments in e-scooter services is subject to the following Condition.

Condition 1. *To have* $A^{\mathscr{M}*} > 0,$ *it should result that* $\alpha - \beta(c_F + c\theta) > 0$ *and* $2c_A\beta - \delta^2 > 0.$

The term $\alpha - \beta(c_F + c\theta)$ explains the necessity having a sufficiently high market potential, which should indicate the main motivations to invest in e-scooters. Indeed, such a value must be compared to the weaknesses and threats of dealing with e-scooters, given by consumers' sensitivity to price, as well as the possible impact of both the logistics challenges and the cost of improper e-scooter usage. Furthermore, the term $2c_A\beta - \delta^2$ informs the difficulties of making people aware of the benefits linked to e-scooters. Being oriented to the maximization of their subjective utility, consumers think in a myopic way, which can be interpreted hereby as consumers' decisions of using e-scooters according to their sensitivity to price and the logistics implications rather than according to the overall services received. For example, a consumer who needs an e-scooter and finds an available e-scooter with a low battery level and dirty handlebar will still purchase the service according to her sensitivity to price and logistics challenges. A further discussion can be made for $c_I,$ for which it results that $\frac{\partial A^{\mathscr{M}*}}{\partial c_I} = -\frac{u_G c_F \delta \gamma \beta d}{c_I^2(2\beta c_A - \delta^2)} < 0;$ this result depends on $\frac{\partial I^{\mathscr{M}*}}{\partial c_I} < 0,$ implying that increasing the values of c_I induces G to invest less in infrastructure, hence discouraging investments in $A^{\mathscr{M}}$. Accordingly, E cannot invest and offer e-scooter services without a proper city infrastructure. Finally, the optimal price displayed in $p^{\mathscr{M}*}$ indicates that E should consider the relationship between both the advantages and the costs associated with e-scooter services. While the numerator is positive according to Condition 1, the positivity of the numerator is ensured when the following Condition applies.

Condition 2. *To have* $p^{\mathscr{M}*} > 0,$ *it should result that* $\frac{c_F d\gamma u_G - c_I(c_F + c\theta)}{c_I c_A} > \frac{\alpha}{\delta^2 + c_A\beta}.$

Condition 2 indicates that the economic benefits e-scooter service guarantee to players should be higher than the potentiality offered by the market per se. That is, although a market for e-scooter exists, the entire business model can be successful only when the price is fixed according to the players' economics, including the saving costs for logistics for E and the utility induced by the society using the infrastructure for G.

Corollary 1. *The optimal demand associated with G and E are respectively given by*

$D_G^{\mathscr{M}*} = \frac{c_A\beta[c_F d\gamma u_G\beta + c_I(\alpha - \beta(c_F + c\theta))]}{c_I(2c_A\beta - \delta^2)}$ *and*

$$D_E^{\mathscr{M}*} = \frac{c_A\beta[c_F d\gamma u_G\beta + c_I(\alpha - \beta(c_F + c\theta))] + u_G\gamma^2(2\beta c_A - \delta^2)}{c_I(2c_A\beta - \delta^2)}.$$

Proof. *See the Online* Appendix A. □

Using Condition 1, one can easily determine that the demand for both players is always positive. This highlights that both have the change to pursue their maximization objectives since the market always exists. Among the various parameters that one can analyze, it is interesting to check the role of u_G and γ; in fact, while the positive impact that they provide to $D_G^{\mathscr{M}*}$ is clear and intuitive, the benefits that they provide to the demand of e-scooters service informs on the partial complementarity that exists between them. That is, a person accessing to the e-scooter service also uses the urban infrastructure at the same time. In contrast, a person accessing to the infrastructure through his car does not use the e-scooter service but, rather, gets influenced by the e-scooter usages by other people.

Proposition 2. *The optimal utility for G and the optimal profits for E are respectively given by* $U_G^{\mathscr{M}*} = \frac{c_A\beta(u_E - \theta u_G)[c_F d\gamma u_G\beta + c_I(\alpha - \beta(c_F + c\theta))]}{c_I(2c_A\beta - \delta^2)} + \frac{\gamma^2 u_G^2}{2c_I}$ *and* $\Pi_E^{\mathscr{M}*} = \frac{c_A[c_F d\gamma u_G\beta + c_I(\alpha - \beta(c_F + c\theta))]^2}{2c_I^2(2c_A\beta - \delta^2)}.$

Proof. *See the Online* Appendix A. □

Proposition 2 highlights the interplay between the optimal strategies set by the government and the e-scooter company. Specifically, it explains the optimal utility for the government and the optimal profits for the e-scooter company achieved when each player implements their respective optimal strategies derived in Proposition 1. According to Condition 1, E's profits are always positive and are influenced by $A^{\mathscr{M}}$, which determines their structure. Specifically, E operates in a market where e-scooter consumers are more sensitive to price than to the e-scooters' capacity and maintenance, while the management of the e-scooter fleet and related operations comes with significant expenses. These are indeed the conditions under which e-scooter firms currently work. This observation is supported by the report from The Portland Bureau of Transportation, 2020, the agency responsible for maintaining Portland's transportation infrastructure, which highlights that e-scooters are comparatively more expensive than other active transportation options. Price-sensitive users are likely to decrease their usage if prices increase (Brezovec and Hampl, 2021). Moreover, the predominant costs incurred today arise from operations and charging, and the additional expenses are substantial. This is due to the daily routine of e-scooter providers, which typically involves collecting the e-scooters, transporting them to a central facility for battery charging, maintenance, and repairs, and then redistributing them for the next day (Schellong et al., 2019). On the other hand, G can only achieve positive optimal utility when specific conditions apply in the presence of e-scooters.

Condition 3. *A sufficient condition for G to gain positive optimal utility is that* $u_E - \theta u_G > 0.$

According to Condition 3, G's utility is damaged when consumers engage in inappropriate behaviors using the e-scooter, which generate issues in managing the urban infrastructure. However, people using e-scooters are still able to achieve their mobility objective, leading to a general improvement in G's utility. Consequently, G evaluates a trade-off between the utility lost because of improper behaviors and the utility gained due to people's mobility. However, Condition 3 is not a necessary condition since the solution to such a trade-off is not guaranteed. Rather, G needs to verify the following condition.

Condition 4. *When condition 3 cannot be verified, a necessary and sufficient condition for G to gain positive optimal utility is that* $\frac{\gamma^2 u_G^2(2c_A\beta - \delta^2)}{2c_A\beta[c_F d\gamma u_G\beta + c_I(\alpha - \beta(c_F + c\theta))]} > \theta u_G - u_E.$

Using the function $D_G^{\mathscr{M}*}$ in the Corollary, one can observe that the inverse of G's demand, $\frac{1}{D_G^{\mathscr{M}*}},$ measures the cost and the investments required to satisfy consumers using the infrastructure, while $\frac{\gamma^2 u_G^2}{2c_I}$ represents the marginal benefits that G obtains when installing a certain level of infrastructure. Accordingly, the benefits induced by G's infrastructure should be higher than the loss of utility from improper consumer behaviors when accessing e-scooter services.

Conditions 3 and 4 highlight the challenge that smart cities face today: The presence of an improper use of e-scooter, θ, can challenge the overall utility that the city wishes to obtain. Therefore, in the subsequent section, we will analyze the possible improvements that firms can obtain when it is possible to mitigate the effect of θ. In fact, one can easily verify that $\lim_{\theta\to 0} u_E - \theta u_G = u_E > 0$ and $\lim_{\theta\to 0} \frac{\gamma^2 u_G^2}{2c_I}\frac{1}{D_G^{\mathscr{M}*}} - \theta u_G + u_E = \frac{\gamma^2 u_G^2 c_I\left(2c_A\beta-\delta^2\right)}{2c_I c_A\beta[c_F d\gamma u_G\beta + c_I(\alpha-\beta c_F)]} + u_E > 0,$ which highlights the urgency of reducing the effect of θ.

4.2. Equilibria of the smart mobility game with blockchain

As in the $\mathscr{M}$-game, G and E play the game à la Nash in the $\mathscr{B}$-game. Accordingly, G sets the optimal infrastructure investments, $I^{\mathscr{B}}$, and E sets the optimal price and e-scooter services, given by $A^{\mathscr{B}}$ and $p^{\mathscr{B}}$, along with the blockchain investments, $B^{\mathscr{B}}$. Accordingly, the equilibria for the $\mathscr{B}$-game are summarized in the proposition below:

Proposition 3. *Assuming an interior solution, the players strategies are given by* $I^{\mathscr{B}*} = \frac{fh+gu_G}{c_I}$, $A^{\mathscr{B}*} = \frac{c_B\delta[c_F d(fh+gu_G)\beta + c_I(\alpha-\beta(c_F+c\theta))]}{c_I\left[(2\beta c_A-\delta^2)c_B - c_A(c\beta\gamma-\eta)^2\right]}$, $B^{\mathscr{B}*} = \frac{c_A(c\beta\gamma-\eta)[c_F d(fh+gu_G)\beta + c_I(\alpha-\beta(c_F+c\theta))]}{c_I\left[(2\beta c_A-\delta^2)c_B - c_A(c\beta\gamma-\eta)^2\right]}$, *and*

$$p^{\mathscr{B}*} = \frac{\left\{\begin{array}{c}\left[c_A\eta((c\beta\gamma-\eta)) - c_B\delta^2\right][c_F(c_I - d(fh+gu_G)) + c\theta c_I] \\ -c_A[c\alpha\gamma c_I(c\beta\gamma-\eta) + c_B(c_F d(fh+gu_G)\beta - c_I(\alpha+\beta(c_F+c\theta)))]\end{array}\right\}}{c_I\left[(2\beta c_A-\delta^2)c_B - c_A(c\beta\gamma-\eta)^2\right]}.$$

Proof. *See the Online Appendix A.* □

Accordingly, G's investments in infrastructure, $I^{\mathscr{B}*}$, are always positive given that both f and h are positive constants. Indeed, when $f < 0$, the $NUM\left[I^{\mathscr{B}*}\right]^2$ must always take positive values to guarantee $I^{\mathscr{B}*} > 0$. Investments in e-scooter services, $A^{\mathscr{B}*}$, are positive and feasible according to the denominator, for which the following condition must apply.

Condition 5. *To have* $A^{\mathscr{B}*} > 0,$ *it should result that* $\left(2\beta c_A - \delta^2\right)c_B - c_A(c\beta\gamma-\eta)^2 > 0$

This condition follows Condition 1 for part $2\beta c_A - \delta^2 > 0$, which turns out to be more restrictive and, consequently, highlights the further difficulties people experience in understanding the benefits of using e-scooters through a verification system like blockchain. The term $c_A(c\beta\gamma-\eta)^2$ explains the improvements obtainable when using blockchain, which are explained by the decreasing costs linked to users' improper behaviors. Moreover, this relationship is further influenced by the parameter η, which denotes people's inclination towards using e-scooters in conjunction with a verification system like blockchain when $\eta > 0$, or their confidence in utilizing e-scooters monitored through blockchain systems when $\eta < 0$, or their indifference towards the presence of blockchain supporting e-scooter services. As a result, in accordance with Condition 5, the benefits associated with the usage of e-scooters are adjusted based on individuals' attitudes towards blockchain implementation and its impact on the overall smart mobility system, which are exemplified by $\left(2\beta c_A - \delta^2\right)c_B$; those should be higher than the benefits obtainable from the presence of blockchain, which is exemplified by $c_A(c\beta\gamma-\eta)^2$. In other words, a business model that offers excellent e-scooter services without harnessing the benefits of blockchain technology can still be viable, whereas a business model that provides extremely poor e-scooters despite having excellent blockchain implementation is unlikely to be appealing or successful.

Instead, according to Condition 1, the numerator of $A^{\mathscr{B}*}$ is always positive. Interestingly, while the investments in e-scooters increase with the presence in the market, it is also boosted by the increasing investments in infrastructure, which are captured by the terms $fh + gu_G$ and c_I. Therefore, when G invests more in infrastructure, E has an attitude to invest more in e-scooters, even when supported by blockchain technology.

Note that Condition 5 allows $p^{\mathscr{B}*}$ and $B^{\mathscr{B}*}$ to have a positive denominator, which implies that the feasibility of these two strategies depends on the sign of their numerators.

Condition 6. *To have* $B^{\mathscr{B}*} > 0,$ *it should result that* $c\beta\gamma - \eta > 0.$

Condition 6 indicates that blockchain should yield positive effects, even when $\eta > 0$. The cases of $\eta < 0$ (which signifies that people are enthusiastic of using e-scooter supported and monitored through blockchain) and $\eta = 0$ (which signifies that people are indifferent to the presence of blockchain when purchasing e-scooter services) make the investments in blockchain always positive and feasible; in contrast, the case $\eta > 0$ (which implies that people are reluctant in renting e-scooters since they are monitored and controlled by blockchain systems) requires that $c\beta\gamma - \eta > 0,$ according to which the benefits offered by blockchain in terms of lower costs associated with improper consumption behaviors are higher than the loss of users' confidence in such a system. When these conditions are met, E's investments in blockchain are positive and, as for the e-scooter investments, increase in both the market, exemplified by $\alpha - \beta(c_F + c\theta)$, as well as both the investments and the benefits of infrastructure, exemplified by $fh + gu_G$.

Regarding the pricing strategy, $p^{\mathscr{B}*}$, all previously identified conditions should apply and interact with each other in a complex way. Specifically, three observations can be made:

1. Assume that $X = fh + gu_G$, represents a proxy to measure the benefits generated by the infrastructure, given the numerator of $I^{\mathscr{B}*}$; hence, $\frac{\partial p^{\mathscr{B}*}}{\partial X} = -\frac{c_F d\left[c_A(\beta c_B + \eta(c\beta\gamma-\eta)) - \delta^2 c_B\right]}{c_I\left((2\beta c_A-\delta^2)c_B - c_A(c\beta\gamma-\eta)^2\right)} < 0,$ which implies that increasing benefits linked to infrastructure leads to a price reduction for e-scooters.
2. The market $\frac{\partial p^{\mathscr{B}*}}{\partial\alpha} = \frac{c_A(\gamma c(c\beta\gamma-\eta) - c_B)}{c_I\left((2\beta c_A-\delta^2)c_B - c_A(c\beta\gamma-\eta)^2\right)} z.gEl; 0 \Leftrightarrow c\beta\gamma - \eta z.gEl; \frac{c_B}{\gamma c}$, where the term $\frac{c_B}{\gamma c}$ is the ratio between costs and benefits of blockchain technology ; accordingly, $\eta \overset{\leq}{>} \frac{c^2\beta\gamma^2 - c_B}{\gamma c}$ indicates that the generally accepted result that increasing market potential leads to increasing prices is unconfirmed when blockchain technology can influence people's behaviors and actions.
3. Considering that

$$\eta \overset{\geq}{<} 0,\ \frac{\partial p^{\mathscr{B}*}}{\partial\eta} = \frac{\left\{\begin{array}{c} c_A[c_I(\alpha-\beta(c\theta+c_F)) + c_F\beta d(fh+gu_G)] \\ \left[c_B\left(2\eta c_A - c\gamma\delta^2\right) + c_A\gamma c(c\beta\gamma-\eta)^2\right]\end{array}\right\}}{c_I\left[(2\beta c_A-\delta^2)c_B - c_A(c\beta\gamma-\eta)^2\right]^2},$$

which one can derive that

$$\eta^* = \frac{\left\{\begin{array}{c} c_A\left(c^2\beta\gamma^2 - c_B\right)\pm \\ \hline \sqrt{c_A c_B(c_A(c_B - c^2\beta\gamma^2) - \gamma^2 c^2(\beta c_A - \delta^2))}\end{array}\right\}}{c\gamma c_A}.$$

Therefore, the optimal price shows increasing or decreasing behavior with respect to η depending on the constant terms $X = fh + gu_G$ and $Y = (u_E - \theta u_G)[c_F dgu_G + c_I(\alpha - \beta(c_F + c\theta))]$.

Corollary 2. *The optimal demand associated with G and E in the* $\mathscr{B}$*-game are respectively given by*

$$D_E^{\mathscr{B}*} = \frac{\left\{\begin{array}{c} c_B\delta^2\{c_F[dX - c_I](1+\beta) + c_I[\beta - c(1+\beta)\theta]\}+ \\ c_A\{-(c\beta\gamma-\eta)[(c_I\beta - c_F(c_I - dX))(1+\beta))\eta+ \\ c_I c\left[(1+\beta)(\alpha\gamma - \eta\theta) - \beta^2\gamma\right]\right]+ \\ c_B(-c_F dX\beta + c_I(\alpha(1+2\beta) + \beta(c_F - 2\beta + c\theta)))\}\end{array}\right\}}{c_I\left[c_A\left(2c_B\beta - (c\beta\gamma-\eta)^2\right) - c_B\delta^2\right]} \quad \text{and}$$

$D_G^{\mathscr{B}*} = \frac{g(fh+\gamma u_G)}{c_I} - \left(\theta - \gamma B^{\mathscr{B}*}\right) D_E^{\mathscr{B}*}.$

Proof. *Substitute the optimal strategies in the demand functions to derive* $D_G^{\mathscr{B}*}$ *and* $D_E^{\mathscr{B}*}$. □

Although it is possible to analytically obtain the optimal demand for G and E, the conditions ensuring the positivity can only be derived numerically. Considering that $DEN\left[D_E^{\mathscr{B}*}\right] > 0$ according to Condition 5, we need to verify that $NUM\left[D_E^{\mathscr{B}*}\right] > 0$ holds as well.

Proposition 4. *The optimal utility for G and the optimal profits for E in the* $B-$*game are given respectively by*

$$\Pi_E^{\mathscr{B}*} = \frac{\left\{\begin{array}{c} 2c_B\beta(fh+gu_G)^2 + c_B(u_E - \theta u_G) \\ \left[c_F d\beta(fh+gu_G) + c_I(\alpha - \beta(c_F + c\theta))\right] \end{array}\right\}}{2c_I^2\left[c_A\left(2c_B\beta - (c\beta\gamma - \eta)^2\right) - c_B\delta^2\right]^2} \text{ and}$$

$$U_G^{\mathscr{B}*} = \frac{\left\{\begin{array}{c} c_B^2 c_I X^2\delta^4 - 2c_A c_B c_I \delta^2\left[c_B\beta\left(2X^2 + Y\right) - X^2(c\beta\gamma - \eta)^2\right] + \\ c_A^2\left\{c_I X^2(c\beta\gamma - \eta)^4 + 4c_B^2 c_I \beta^2\left(X^2 + Y\right) + \right. \\ 2c_B\beta(c\beta\gamma - \eta)\left[c_F^2 d^2 u_G X^2\beta^2\gamma + \right. \\ c_I^2(\alpha - \beta(c_F + c\theta))(u_G((\alpha - c_F\beta)\gamma - \eta\theta) - u_E(c\beta\gamma - \eta)) - \\ c_I X\left[2c_F^2 d u_G \beta^2\gamma - 2X\eta + c_F d\beta((u_G\theta - u_E)\eta - 2u_G\alpha\gamma) + \right. \\ \left.\left.\left. c\beta\gamma(2X + c_F d\beta(u_E + u_G\theta))\right]\right]\right\} \end{array}\right\}}{2c_I^2\left[c_A\left(2c_B\beta - (c\beta\gamma - \eta)^2\right) - c_B\delta^2\right]^2}.$$

Proof. *See the Online* Appendix A. □

According to Conditions 5 and 6 and considering that $DEN\left[\Pi_E^{\mathscr{B}*}\right] > 0$, E's profits are always positive when $u_E - \theta u_G > 0$, that is, when the utility that G gains if people use e-scooters is higher than the utility lost due to a lower usage of the infrastructure in a traditional mobility way. Furthermore, E's profits are still positive even when $u_E - \theta u_G < 0$, conditioned on the fact that the benefits G gains in terms of e-scooter utility and fees to access the city's smart objects are sufficiently high. Interestingly, the viability of positive profits for E is contingent upon the substantial gains achieved by G. In real-world scenarios, this observation holds true as well: cities with inadequate infrastructure and a lack of access to smart objects present limited opportunities for establishing successful smart businesses, regardless of their type and nature. Hence, the presence of these two key elements, namely advanced infrastructure and smart objects, forms the foundation for E's interest in providing e-scooter services in city G.

Unlike E, G's optimal utility can be derived analytically although its analysis is compromised. This is due to the important trade-offs that G has to manage and that link to the impact that $D_E^{\mathscr{B}}$ has on $U_G^{\mathscr{B}}$, whose impact is complicated by the blockchain technology. We will then analyze these relationships numerically in Section 6.

5. The effects of blockchain for smart mobility

In this section, we analyze the effects of blockchain on the smart mobility system under investigation. To do so, we compare the solution derived from the $\mathscr{B}$-game to the solution obtained in the $\mathscr{M}$-game to highlight the benefits and the behavioral changes induced by the adoption of blockchain technology. This involves examining how the players' strategies are modified and how improper user behaviors are detected through the connection to the city's smart objects.

Proposition 5. *Player G always invests more in infrastructure when E adopts blockchain to detect improper user behaviors.*

Proof. *Using the optimal solutions in* $I^{\mathscr{M}*}$ *and* $I^{\mathscr{B}*}$, *it results that* $\Delta_I = I^{\mathscr{M}*} - I^{\mathscr{B}*} = -\frac{fh}{c_I} \lesseqgtr 0 \Leftrightarrow f \gtreqless 0.$ □

Notably, G demonstrates a willingness to increase investment in infrastructure only when the blockchain incorporates hardware oracles, represented by the parameter h, and when the technology ensures a certain payment denoted as $f > 0$, facilitated through smart contracts. As a consequence, these two factors play a crucial role in shaping G's strategy when the blockchain technology is employed. This finding is particularly significant, as the use of blockchain to detect and mitigate improper user behavior leads to modifications in G's payoff (see $U_G^{\mathscr{B}*}$). However, the task made by the blockchain has no effect on G's strategies, which depend on the blockchain's capacity to transform the city objects and the related infrastructure into hardware oracles rather than on its capability to detect improper user behaviors of the infrastructure. When $h = f = 0$, G does not modify the investments in infrastructure in the presence of blockchain. Finally, $f < 0$ represents the only case in which G invests less in infrastructure since he has lower resources to invest due to the incentive supplied to E. At the same time, G expects E to do more (e.g., effective blockchain and better e-scooter services) because she gets paid by G.

Proposition 6. *Player E always invests more in e-scooter services when adopting blockchain to detect improper user behaviors.*

Proof. *See Online* Appendix A. □

According to Proposition 6, E always has an incentive to invest more in e-scooter capacity when the blockchain complements the service system. Interestingly, when $\eta < 0$ ($\eta > 0$) and people are then in favor (against) the use of blockchain to monitor improper user behaviors, E is encouraged to invest more (less) in e-scooter services. Therefore, E should decide the amplitude of the e-scooter investments by estimating users' willingness to monitor themselves and others, detect improper behaviors in using the e-scooters, and eventually penalize users. This result opens windows for future research in the field of users' acceptance of digital technologies like blockchain to keep track of behaviors.

Remark 1. Player E does not invest in blockchain when $c\beta\gamma = \eta$.

As one can see from Condition 6, $c\beta\gamma - \eta > 0$ is an important condition to render blockchain strategically suitable, which results in $B^{\mathscr{B}*} = 0$ when $c\beta\gamma = \eta$.

Proposition 7. *Player E always charges a lower price for the e-scooter service when adopting blockchain to detect improper user behaviors.*

Proof. *See Online* Appendix A. □

The analysis of the prices suggests that E charges lower prices when the blockchain is in use, which is most likely driven by the capacity that the technology has to mitigate improper behaviors by users. This is also followed by the cost savings induced by better urban infrastructure, which leads to lower prices for users. Indeed, $\eta < 0$ ($\eta > 0$) suggests that people are in favor (against) the use of blockchain to monitor their behaviors, as well as the other user behaviors; hence, E offers an advantage (disadvantage) to people in terms of low (high) prices as the users signal their willingness to adopt correct (incorrect) and honest (dishonest) behaviors when using the e-scooters. In other words, E is encouraged to invest more (less) in e-scooter service. This result makes a valuable contribution to the ongoing debate concerning the estimation of social outcomes and the overall welfare and security of cities when leveraging digital technologies. Our findings highlight that the extent of social benefits, particularly in terms of people's ability to access urban mobility infrastructure and smart mobility services effectively, is contingent on their willingness to embrace responsible behaviors.

Remark 2. When $c\beta\gamma = \eta$ and h=0 the $M-$*game* and the $B-$*game* are identical.

From the proofs of Propositions 5-7, one obtains $\Delta_I = \Delta_A = \Delta_p = B = 0$, leading to the finding that the $M-$*game* and the $B-$*game* are identical. Therefore, the players should be aware that $c\beta\gamma - \eta > 0$ and

$h > 0$ are necessary conditions to guarantee that the adoption of blockchain technology modifies their strategies and economic behaviors.

Proposition 8. *Player E always sells more accesses to e-scooter service when adopting blockchain to detect improper users' behaviors.*

Proof. *See Online* Appendix A. ☐

The analysis of users' access to the e-scooter service reveals that the presence of blockchain technology elicits a higher willingness among people to purchase more services due to the enhanced sense of security and protection it provides. Compared to traditional systems, blockchain ensures greater safety, and its continuous monitoring of user behaviors is perceived positively, particularly in the context of potential risks associated with low e-scooter service quality that may endanger users' health. This observation is evident from the negative coefficient ($\eta < 0$), which signifies that users are even more inclined to embrace the presence of blockchain for monitoring user behaviors. It is important to note that this result is closely associated with the presence of smart infrastructure, represented by h, and the incentive (f) that G receives when blockchain is implemented. Thus, even in scenarios where there might be some reluctance towards adopting blockchain ($\eta > 0$), a well-designed and structured urban infrastructure creates a perception among users that e-scooter services can be purchased and utilized with a high level of safety and security, thanks to the physical infrastructure facilitated by the city. Overall, the incorporation of hardware oracles significantly enhances access to smart mobility services, resulting in cost savings related to logistics and service operations, ultimately leading to lower prices for users.

Proposition 9. *Player G gains greater access to the urban infrastructure when adopting blockchain to detect improper user behaviors.*

Proof. *See Online* Appendix A. ☐

The analysis of access to the urban mobility shows an increasing demand for mobility when blockchain is in place when $f > 0$. This is most likely linked to the increased level of security that people feel as blockchain preserves and mitigates improper e-scooter user behaviors. Also for the access to the urban infrastructure, it results that $\eta < 0$ enables the use blockchain and the activation of hardware oracles, especially for high values of h. When the incentive f favors G, the adoption of blockchain increases the access to urban mobility due to increasing quality of the infrastructure, even in case of $\eta > 0$.

Claim 1. *The players' payoffs heavily depend on all the models' parameters.*

Proof. *See Online* Appendix A. ☐

According to Claim 1, the comparison of the players' payoffs in the two games heavily depends on all parameter values, even when assuming that $\eta = c\beta\gamma$. Relaxing this assumption will inevitably lead to a more complex computations. In Online Appendix A, we report Example 1, which refers to computing $\Delta\Pi_E = \Pi_E^{\mathscr{M}*} - \Pi_E^{\mathscr{B}*}$ and assuming that $c\beta\gamma - \eta > 0$. One can see that the players' payoffs heavily depend on the constellation of the parameter values and, consequently, we shall proceed numerically to derive some managerial insights and prescriptions

6. Numerical analysis on the economic benefits of blockchain

Although we derive a full analytical analysis of the games, we conduct hereby a numerical analysis with a dual objective of identifying the specific regions and scenarios in which the adoption of blockchain technology leads to improved economic outcomes for firms; furthermore, we perform a sensitivity analysis of the parameter values to demonstrate the robustness of our results. To achieve these goals, we set the parameter values using well-established parameter sets from the literature, which have been utilized in similar research endeavors (e.g., Biswas et al., 2022). Specifically:

$$\mu_G = 1, \mu_E = 0.2, c = 0.5;\ \alpha = 0.5;\ \beta = 0.7;\ \eta = 0.1;\ \delta = 0.2;\ d = 0.3;\ \theta = 0.1;\ f = 0.01;\ c_F = 0.4;\ c_B = 1;\ c_A = 0.2;\ c_I = 1;\ g = 1;\ h = 0.5.$$

These parameter values represent our benchmark, which will later be modified to analyze the players' profits and derive a sensitivity analysis of our findings.

6.1. Impact of blockchain for the players' profits

In this section, we focus on three parameters to analyze the firms' profits, whose importance emerges from the analytical analysis and is highlighted in Conditions 5 and 6. Specifically, we focus on the following.

1) The consumers' perception of using e-scooters while being monitored and, eventually, penalized by the blockchain system in case of improper usage of e-scooters, η, such that $\eta \in [-0.2, 0.2]$. $\eta = -0.2$ indicates that consumers accommodate and encourage the use of blockchain to monitor e-scooter usage, which would end up in more efficient e-scooters and safe city; when $\eta = 0.2$, people are reluctant to access e-scooters complemented by blockchain technology that monitors and penalizes non-diligent behaviors; finally, $\eta = 0$ signifies that users are indifferent to the existence of a monitoring system managed through blockchain technology and access to e-scooter services by only evaluating the price and the e-scooter service itself.
2) The fee associated with the use of hardware oracles, f, such that $f \in [-0.03, 0.03]$. When $f > 0$, the fee is paid from the e-scooter company to the city, while the fee is paid from thecity to the e-scooter company when $f < 0$. In the former, the city pretends that the e-scooter company pays the fees since she gets access to the city's objects, especially when they are already smart and the switch to hardware oracles is easy and natural; in the latter, the e-scooter company requests a payment by the city to convert the physical objects into hardware oracles. Finally, $f = 0$ highlights the case in which no compensation scheme is adopted by players, independent of the status and the usage of the city's objects as hardware oracles.
3) According to Condition 6, the triple $c\beta\gamma$ guarantees that the $\mathscr{B}$-game is feasible. Therefore, we focus on the parameter β to derive the figures of how players' profits are influenced by the adoption of blockchain technology, while the parameters c and γ are kept at the benchmark level. Therefore, $\beta \in [0.5, 0.9]$ captures the changes in the consumers sensitivity to price and indicates the firms' convenience and preferences in adopting the blockchain technology given the consumers' sensitivity to price change. Note that modifying either c or γ would have given a qualitatively equivalent finding, as it results from the sensitivity analysis reported in the next section.

Setting the aforementioned ranges guarantees that all feasibility conditions are met. Hence, Fig. 2 displays the changes in the players' optimal payoffs in the space (β, η, f); furthermore, we report the surfaces inside which the players prefer the adoption of blockchain technology (e.g., Fig. 2a and b), as well as the Pareto-improving region (e.g., Fig. 2c), showing the conditions under which both players prefer the adoption of blockchain technology embedding smart contracts that can be activated through hardware oracles. According to Fig. 2, the following observations can be made:

- E' s profits, which are displayed in Fig. 2a, indicate that the fee plays an important role in determining the convenience in implementing the blockchain technology. When the fee takes a negative value, meaning that G incentivizes E to use the city objects as hardware

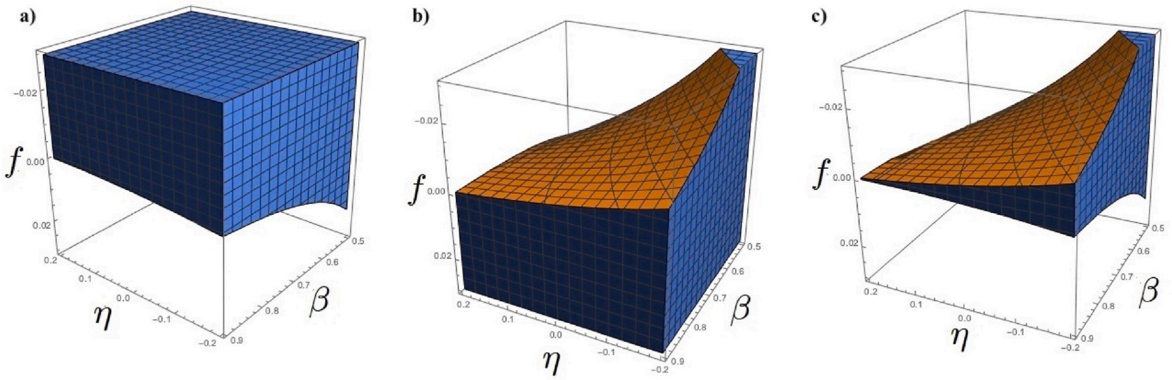

Fig. 2. The solid surface indicate $\Pi_E^{\mathscr{M}*} - \Pi_E^{\mathscr{B}*} < 0$ (a), $U_G^{\mathscr{M}*} - U_G^{\mathscr{B}*} < 0$ (b), and the Pareto-improving region (c).

oracles, E is always willing to complement the e-scooter service with blockchain technology to detect the improper use of the smart mobility. Interestingly, this result is independent of the values taken by β and η. In contrast, when the fee is paid to G for the access granted in accessing the city objects, E does not always find investments in blockchain convenient. Specifically, increasing values of η increase the area in which E's convenience of adopting blockchain increases as well, although the improvement is minimal. Note that moving from negative to positive values for η in Fig. 2a leads to minimal improvement in E's profits when blockchain is adopted. Furthermore, increasing values of β lead to a decreasing willingness for E to implement the blockchain. Although increasing values of β make the overall analysis more robust (e.g., Condition 6 is reinforced), the e-scooter users find the price too high and, consequently, will decrease accesses to the service. Unlike η, β has an important impact on E's profits and, hence, its impact must be carefully analyzed. When $f > 0$, E needs consumers to be highly available to be monitored and controlled through blockchain technology ($\eta < 0$) as well as not to be sensitive to price increases (low β); however, a negative fee penalizes E too much and, consequently, some combinations of low β and negative η will not guarantee that E prefers to invest in blockchain (e.g., the lower part of Fig. 2a is empty).

- The analysis of G's utility, which is reported in Fig. 2b, highlights that his preferences regarding the possible implementation of blockchain technology are reversed with respect to E. In fact, positive values of f grant an economic benefit to G since E gets access to the city objects, like traffic lights and cameras. Interestingly, $f > 0$ makes G economically better off with the adoption of blockchain, independent of the other model parameter values. Hence, this is a sufficient condition to guarantee to G higher utility through blockchain. However, even when $f < 0$, implying that G pays E for implementing a blockchain to control and monitor users' improper behaviors, several combinations of β and η can still grant a chance to increase the utility to G. Specifically, as for E, consumers insensitive to price (low values of β) and users' willingness to be monitored and controlled by blockchain to get better e-scooter services (negative η) make G better off with blockchain, independent of f. Therefore, G has a higher change of benefiting from blockchain (no area of Fig. 2b is empty).
- Fig. 2c shows the Pareto-improving region inside which both players are better off when adopting blockchain. Accordingly, the use of blockchain to activate hardware oracles and detect the improper behaviors adopted by users can be beneficial for both players when $f \simeq 0$, that is, when (most likely) no incentive and/or penalties are in place. This result is positioned among the massive body of literature in coordination mechanisms that sponsors the adoption of incentives to align the players' targets and behaviors (e.g., see Cachon, 2003) and is also an ingredient to populate the smart contracts for all stakeholders involved (e.g., De Giovanni, 2022b). Our results demonstrate that the smart contracts should be used as a digital technology to avoid opportunistic behaviors; in our framework, the players implement the blockchain to mitigate opportunistic behaviors adopted by e-scooter users rather than for their own behaviors. Therefore, while the existing literature uses the smart contracts to detect and mitigate possible risks of opportunistic behaviors of a firm that plays the game, in our framework, the smart contract should play a role from the users' side and activate some payments when improper behaviors are undertaken. Furthermore, when $f < 0$, a Pareto-improving situation can be obtained in all cases in which G is better off when blockchain is adopted. In constrast, a Pareto-improving region also exists when $f > 0$ and requires E to be better off with blockchain technology.

6.2. Sensitivity analysis

In this section, we carry out a sensitivity analysis to check the robustness of our findings. Hence, we start from the solution obtained by using the benchmark parameter values that have been previously mentioned. Then, we run a simulation by deriving the optimal strategies, demand, and payoff functions when the parameter values change with the step 0.05. The full set of simulations is reported in the Online Appendix B. For each parameter value, the parameters displayed in the main columns of Tables B1-B4 have been increased by 0.05, while all other parameters have been kept at the benchmark value. Every time a parameter is changed, we report the numerical outcomes of strategies, demand, and players' payoffs. We focus on all of the parameters, except β, η, and f, for which we have already developed an exhaustive analysis in the previous section. According to the results we obtained, we can derive the following set of additional information:

- Increasing values of the city's utility deriving from smart mobility positively influences G's profits and investments in infrastructure, while making E completely indifferent in terms of strategies and payoffs. This finding is independent of the use of blockchain to detect improper user behaviors. On the contrary, as the utility from traditional mobility increases, it leads to a favorable outcome for all participants and fosters positive sentiments. In such a scenario, all players will enhance their investments in their respective strategies without negatively affecting the demand, even if there is a pricing increase. This observation underscores the presence of compensating effects. Moreover, these implications hold true when the values of marginal usages of urban infrastructure, g, increase.
- As the costs associated with dishonest user behaviors and their frequency increase, E is incentivized to invest more in e-scooter services while simultaneously reducing the price to maintain relatively stable profits. In contrast, G's strategies and profits are adversely affected only by the frequency of improper and dishonest behaviors, which can be mitigated through the monitoring potentials of blockchain

technology, represented by the parameter γ. Remarkably, this parameter motivates all players to engage more actively, highlighting the potential for a recovery effect facilitated by blockchain technology. Based on the simulation results, it can be inferred that higher values of γ enable both players to recover the payoffs lost due to dishonest behaviors and enhance security. Additionally, it is interesting to note that when blockchain is implemented, G's profits increase as the cost of improper user behaviors rises, owing to a lower demand for e-scooter service and, consequently, a higher reliance on traditional mobility.

- Increasing values of both the market potential, α, and users' sensitivity to the e-scooter service, δ, generate positive effects in strategies, demand, and players' payoff, with higher amplitude for the $\mathscr{B}$-game than for the $\mathscr{M}$-game;
- There is a clear trade-off between the maintenance cost associated with the logistics network, c_F, and the possible improvements linked to the urban infrastructure, d. Note that E can yield important operational improvements when the urban infrastructure is well managed, suggesting the need to consider a possible incentive that E grants to G according to the investments in urban infrastructure. Moreover, an efficient logistics network induces the e-scooters firm to invest less in e-scooter and, at the same time, to invest more in blockchain technology.
- Increasing values of the overall effect of investments in the players' payoff functions, denoted by c_B, c_I, and c_A, result in decreasing payoffs, contingent on the relationships between the player and their respective strategies.

Our findings retain their validity and robustness across various other parameter values and ranges beyond those presented in profit-sharing. The authors are ready to provide additional simulations and/or the Mathematica file used for sensitivity analysis upon request. Furthermore, the authors provide some special cases in Online Appendix C, D, and E, to obtain more insights from the research.

7. Managerial implications

Based on our analytical and numerical findings, we have identified several managerial recommendations that decision-makers and firms can consider when operating within a similar framework. These recommendations are as follows.

1. When e-scooter firms aim to collaborate with cities to enhance the user experience and address improper user behaviors, the mere implementation of blockchain technology is insufficient. The investments in infrastructure by cities are not influenced by the use of blockchain alone. Instead, e-scooter firms should leverage blockchain technology to transform the cities' infrastructure and related objects into smart objects. This transformation entails integrating hardware oracles into the blockchain framework. By converting the infrastructure, cities can receive payments, likely in the form of tokens and cryptocurrencies, granting e-scooter firms access to improved infrastructure and increased opportunities for optimizing the e-scooter logistics network.
2. The implementation of blockchain technology compels e-scooter firms to invest more in service capacity, contingent upon the detection rate and users' acceptance of digital technologies. The choice of the appropriate blockchain technology framework depends heavily on these two factors. Ideally, the best framework for implementing blockchain technology and investing in hardware oracles is characterized by a high detection rate, favorable users' acceptance, and minimal fees imposed by the city to access smart objects.
3. The adoption of blockchain technologies for enhanced e-scooter services necessitates a revision of the pricing strategy associated with the service. Users who utilize e-scooter services diligently and responsibly and are willing to be monitored and governed by the blockchain should be rewarded with more affordable access to the service. Reluctance among users to be monitored by the blockchain may signal a propensity for dishonest and improper behavior, thus justifying an increase in the e-scooter service price.
4. In general, the adoption of blockchain technology instills a sense of safety and security among users compared to traditional systems. Consequently, the demand for e-scooters is expected to increase when blockchain is adopted and users accept its presence for behavior monitoring. The detection of improper behaviors results in a more efficient and safer overall service system, including reduced instances of damaged e-scooters requiring maintenance. However, it is important to note that the use of blockchain does not directly impact urban mobility, as the decision to invest in infrastructure remains independent of blockchain implementation.
5. E-scooter firms and cities may hold differing opinions regarding the adoption of blockchain, particularly concerning payments. This can involve the city incentivizing the installation of effective blockchain technology to capture improper behaviors or the e-scooter firm compensating the city for accessing city objects. As both aspects are critical to blockchain technology's success, it is recommended that either no payment or minimal payments be planned to ensure equitable benefits for all stakeholders involved.
6. Enhanced urban infrastructure, encompassing dedicated e-scooter lanes, suitable parking facilities, and seamless connectivity, plays a pivotal role in shaping a favorable user experience. This improved infrastructure fosters convenience, safety, and efficiency, thereby appealing to a larger audience, encouraging the adoption of e-scooters as a preferred mode of transportation. However, it is worth noting that certain types of infrastructure investments may hinder people from embracing e-scooters. Therefore, collaborative efforts between cities and smart mobility firms are necessary to jointly define the most appropriate infrastructure types that can effectively leverage the full advantages of smart mobility systems.
7. The government's proactive actions on infrastructure and regulation pushes the e-scooter company to invest more in compliance technologies, such as blockchain, to ensure safer and more responsible usage of their services. This does not only align the company with public regulations but also improves overall operational efficiency. It creates a sustainable environment where profitability and public welfare coexist.

8. Conclusions

This study employs a game theory approach to analyze the benefits that e-scooters can offer to cities in enhancing smart mobility, as well as the drawbacks arising from their inappropriate use. Such improper behavior includes activities like double-riding and failure to wear helmets, which can have detrimental effects on both the city and the e-scooter firm. Hence, we evaluate whether the adoption of blockchain technology with hardware oracles can address these issues and discourage improper user behavior. The latter not only hinder the optimal utilization of the city's infrastructure but also result in additional costs for the e-scooter firm when the scooters are not used correctly. In the games that we devised, the city determines the extent of urban infrastructure required to ensure safe mobility throughout the territory, while the e-scooter service firm is responsible for deciding the capacity of the e-scooter sharing system and setting the rental price. Notably, this study stands out as the first to introduce hardware oracles into smart mobility frameworks using blockchain technology. Furthermore, no previous research has explored the implementation of this technology specifically for e-scooter sharing systems, employing game theory to analyze the competition dynamics between the city and the firm.

Our findings indicate that the adoption of blockchain technology consistently influences the strategies employed by e-scooter firms. However, its impact on the city's investments in infrastructure only occurs when the blockchain activates city objects (e.g., cameras, traffic lights) as hardware oracles, enabling the city to provide more effective urban infrastructure. This becomes feasible when the hardware oracles generate tokens and/or cryptocurrencies for the city. Conversely, e-scooter firms need to adjust their investments in service capacity based on users' willingness to embrace self-control and accept blockchain for monitoring purposes. Firms should also detect and penalize any improper user behavior to enhance the security of e-scooter services. The interplay among these factors determines the extent of investments in blockchain technology.

Furthermore, users who demonstrate diligent and proper behavior when using e-scooter services should be rewarded with lower service prices. Conversely, users who exhibit reluctance toward being monitored by blockchain technology may exhibit a predisposition toward dishonest and improper behaviors. To discourage such behaviors, e-scooter firms can increase the service price. Consequently, the adoption of blockchain technology can lead to an increase in the demand for e-scooter services, as the detection and mitigation of improper usage behaviors result in more efficient, safer, and well-functioning e-scooter systems. However, the decision to implement blockchain technology in the e-scooter service depends on the fees associated with accessing city objects as hardware oracles and the incentives provided by the city for installing blockchain systems that facilitate the transition from city objects to hardware oracles. The presence of a reward-penalty mechanism reduces the likelihood of both players engaging in a blockchain system. Instead, the e-scooter service should consider engineering smart contracts that penalize dishonest user behaviors rather than viewing blockchain solely as a technology for activating smart contracts.

It is worth acknowledging that this research has limitations that can inspire future investigations in this domain. While this study supports the use of blockchain to detect and penalize improper e-scooter user behaviors, there are various other types of improper and dishonest behaviors exhibited by residents, tourists, and visitors. Future research should explore novel approaches leveraging blockchain technology and related oracles to mitigate such behaviors. Additionally, this study primarily focuses on payments that penalize either the city or the e-scooter firm based on accessibility. Future studies can explore mechanisms involving other factors, such as tourist flows in the city, and investigate collaborative strategies between players, where the city supports investments in blockchain technology. Similarly, future research could explore other ways governments may influence demand, such as through public awareness campaigns that promote sustainable transport options, introducing regulations that favor e-scooters over other transport modes (e.g., congestion zones), or implementing tax breaks for companies that operate e-scooter fleets. These strategies could further enhance the adoption of e-mobility without direct subsidies to users. Furthermore, future studies could incorporate a detailed fee structure that the government charges and that is based on fleet size, docking space requirements, or company profits: these mechanisms could offer further insights into the financial interactions between the government and mobility providers. Our study also reveals that utilizing hardware oracles to detect improper behaviors can reduce their frequency. Future research can expand upon this by exploring the activation of software, human, inbound, and outbound oracles through blockchain. Furthermore, further investigation is necessary to address the issue of digital technology acceptance when attempting to control and monitor individuals' behaviors. These research avenues are currently being explored by the authors.

CRediT authorship contribution statement

Behzad Maleki Vishkaei: Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Pietro De Giovanni:** Writing – original draft, Supervision, Software, Methodology, Funding acquisition, Conceptualization.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijpe.2025.109533.

Data availability

No data was used for the research described in the article.

References

Ahadi, R., Ketter, W., Collins, J., Daina, N., 2023. Cooperative learning for smart charging of shared autonomous vehicle fleets. Transp. Sci. 57 (3), 613–630.

Amar, H.M., Basir, O.A., 2018. A game theoretic solution for the territory sharing problem in social taxi networks. IEEE Trans. Intell. Transport. Syst. 19 (7), 2114–2124.

Auer, S., Nagler, S., Mazumdar, S., Mukkamala, R.R., 2022. Towards blockchain-IoT based shared mobility: car-sharing and leasing as a case study. J. Netw. Comput. Appl. 200, 103316.

Bai, S., Jiao, J., 2020. Dockless e-scooter usage patterns and urban built environments: a comparison study of Austin, TX, and Minneapolis, MN. Travel Behav. Soc. 20, 264–272.

Baum, M., Buchhold, V., Sauer, J., Wagner, D., Zündorf, T., 2023. ULTRA: unlimited transfers for efficient multimodal journey planning. Transp. Sci.

Biswas, D., Jalali, H., Ansaripoor, A.H., De Giovanni, P., 2022. Traceability vs. sustainability in supply chains: the implications of blockchain. Eur. J. Oper. Res.

Brezovec, P., Hampl, N., 2021. Electric vehicles ready for breakthrough in MaaS? Consumer adoption of e-car sharing and e-scooter sharing as a part of mobility-as-a-service (MaaS). Energies 14 (4), 1088.

Bui, K.H.N., Jung, J.J., 2018. Cooperative game-theoretic approach to traffic flow optimization for multiple intersections. Comput. Electr. Eng. 71, 1012–1024.

Cachon, G.P., 2003. Supply chain coordination with contracts. Handbooks in. Operations Research and Management Science: Supply Chain Management/North Holland.

Calandra, D., Secinaro, S., Massaro, M., Dal Mas, F., Bagnoli, C., 2023. The link between sustainable business models and blockchain: a multiple case study approach. Bus. Strat. Environ. 32 (4), 1403–1417.

Castiglione, M., Comi, A., De Vincentis, R., Dumitru, A., Nigro, M., 2022. Delivering in urban areas: a probabilistic-behavioral approach for forecasting the use of electric micromobility. Sustainability 14 (15), 9075.

Chang, A.Y., Miranda-Moreno, L., Clewlow, R., Sun, L., 2019. Trend or Fad: Deciphering the Enablers of Micromobility in the US.

Ciari, F., Balac, M., Balmer, M., 2015. Modelling the effect of different pricing schemes on free-floating carsharing travel demand: a test case for Zurich, Switzerland. Transportation 42, 413–433.

De Bortoli, A., Christoforou, Z., 2020. Consequential LCA for territorial and multimodal transportation policies: method and application to the free-floating e-scooter disruption in Paris. J. Clean. Prod. 273, 122898.

De Giovanni, P., 2020. Blockchain and smart contracts in supply chain management: a game theoretic model. Int. J. Prod. Econ. 228, 107855.

De Giovanni, P., 2022a. Blockchain technology applications in businesses and organizations. IGI Global. https://doi.org/10.4018/978-1-7998-8014-1.

De Giovanni, P., 2022b. Leveraging the circular economy with a closed-loop supply chain and a reverse omnichannel using blockchain technology and incentives. Int. J. Oper. Prod. Manag. 42 (7), 959–994.

Demir, E., Bektaş, T., Laporte, G., 2014. A review of recent research on green road freight transportation. Eur. J. Oper. Res. 237 (3), 775–793.

Emami, M., Haghshenas, H., Talebian, A., Kermanshahi, S., 2022. A game theoretic approach to study the impact of transportation policies on the competition between transit and private car in the urban context. Transport. Res. Pol. Pract. 163, 320–337.

Gosele, M., Sandner, P., 2019. Analysis of blockchain technology in the mobility sector. Forsch. Im. Ingenieurwes. 83 (4), 809–816.

Gössling, S., 2020. Why cities need to take road space from cars-and how this could be done. J. Urban Des. 25 (4), 443–448.

Hasija, S., Shen, Z.J.M., Teo, C.P., 2020. Smart city operations: Modeling challenges and opportunities. Manuf. Serv. Oper. Manag. 22 (1), 203–213.

Helo, P., Hao, Y., 2019. Blockchains in operations and supply chains: a model and reference implementation. Comput. Ind. Eng. 136, 242–251. https://www.portland.gov/sites/default/files/2020-04/pbot_e-scooter_01152019.pdf.

Khan, Z., Koubaa, A., Benjdira, B., Boulila, W., 2023. A game theory approach for smart traffic management. Comput. Electr. Eng. 110, 108825.

Kim, M., Lee, J., Park, K., Park, Y., Park, K.H., Park, Y., 2021. Design of secure decentralized car-sharing system using blockchain. IEEE Access 9, 54796–54810.

Li, Y., Chen, S., Hu, L., Liang, Z., Jiang, Y., Tang, Y., 2021. Simulation-optimization for station capacities, fleet size, and trip pricing of one-way electric carsharing systems. J. Clean. Prod. 321, 129035.

Liu, Q., Yang, J., Guo, Q., Huang, J., Wang, J., 2018. Game analysis on the development of shared bicycle in Xi'an. In: CICTP 2018: Intelligence, Connectivity, and Mobility. American Society of Civil Engineers, pp. 628–636.

Lopez, D., Farooq, B., 2020. A multi-layered blockchain framework for smart mobility data-markets. Transport. Res. C Emerg. Technol. 111, 588–615.

Machado, C.A.S., de Salles Hue, N.P.M., Berssaneti, F.T., Quintanilha, J.A., 2018. An overview of shared mobility. Sustainability 10 (12), 4342.

Magsino, E.R., Ching, G.R.C., Espiritu, F.M.M., Go, K.D., 2023. A game theory-based pricing technique for ridesharing pairings. In: 2023 1st International Conference on Advanced Innovations in Smart Cities (ICAISC). IEEE, pp. 1–5.

Nair, R., Miller-Hooks, E., 2011. Fleet management for vehicle sharing operations. Transp. Sci. 45 (4), 524–540.

Pu, S., Lam, J.S.L., 2023. The benefits of blockchain for digital certificates: a multiple case study analysis. Technol. Soc. 72, 102176.

Rust, R.T., Thompson, D.V., Hamilton, R.W., 2006. Defeating feature fatigue. Harvard Business Review 84 (2), 37–47.

Schellong, D., Sadek, P., Schaetzberger, C., Barrack, T., 2019. The promise and pitfalls of e-scooter sharing. Europe 12 (15).

Soppert, M., Steinhardt, C., Müller, C., Gönsch, J., 2022. Differentiated Pricing of Shared Mobility Systems Considering Network Effects.

Sun, Q., He, Y., Wang, Y., Ma, F., 2019. Evolutionary game between government and ride-hailing platform: evidence from China. Discrete Dynam Nat. Soc. 2019. Article 2378591.

The Portland Bureau of Transportation, 2020. 2018 E-scooter findings report. Available at: The World Bank. (2016). Toward Sustainable Mobility https://www.worldbank.org/en/topic/transport/brief/towards-sustainable-mobility.

Wang, K., Qian, X., Fitch, D.T., Lee, Y., Malik, J., Circella, G., 2023. What travel modes do shared e-scooters displace? A review of recent research findings. Transp. Rev. 43 (1), 5–31.

Wang, W., Zhang, Y., Feng, L., Wu, Y.J., Dong, T., 2020. A system dynamics model for safety supervision of online car-hailing from an evolutionary game theory perspective. IEEE Access 8, 185045–185058.

Yang, H., Bao, Y., Huo, J., Hu, S., Yang, L., Sun, L., 2022. Impact of road features on shared e-scooter trip volume: a study based on multiple membership multilevel model. Travel Behav. Soc. 28, 204–213.

Yang, X., Li, W., 2020. A zero-knowledge-proof-based digital identity management scheme in blockchain. Comput. Secur. 99, 102050.

Zardini, G., Lanzetti, N., Guerrini, L., Frazzoli, E., Dorfler, F., 2021. Game theory to study interactions between mobility stakeholders. In: 2021 IEEE International Intelligent Transportation Systems Conference (ITSC). IEEE, pp. 2054–2061.

Zhang, W., Buehler, R., Broaddus, A., Sweeney, T., 2021. What type of infrastructures do e-scooter riders prefer? A route choice model. Transport. Res. Transport Environ. 94, 102761.

Zhao, D., Wang, D., Wang, B., 2020. Research on a shared bicycle deposit management system based on blockchain technology. J. Adv. Transp. 2020. Article 1389261.

Zhou, C., Li, X., Chen, L., 2023. Modelling the effects of metro and bike-sharing cooperation: cost-sharing mode vs. information-sharing mode. Int. J. Prod. Econ. 261, 108842.

Zuniga-Garcia, N., Juri, N.R., Perrine, K.A., Machemehl, R.B., 2021. E-scooters in urban infrastructure: understanding sidewalk, bike lane, and roadway usage from trajectory data. Case Stud. Trans. Policy 9 (3), 983–994.