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CASE STUDY AND APPLICATION

Merging transport network companies and taxis in Curitiba's BRT system

Rafael Milani Medeiros[1] · Fábio Duarte[2] · Iva Bojic[3] · Yang Xu[4] · Paolo Santi[2] · Carlo Ratti[2]

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Abstract

The Brazilian city of Curitiba became known around the world for pioneering bus rapid transit (BRT) in the 1970s. Five decades later, public transport ridership is declining on the city's bus-based system. One-person car trips and car ownership are soaring, and services provided by transport network companies rapidly proliferate and then disappear as congestion worsens and expands across the road network. This was the macro-scale scenario for mobility and modal trends in Curitiba until COVID-19 brought things to a screeching halt in 2020. The widespread use of information and communication technologies has allowed taxi and car ride-hailing transport network schemes to emerge while blurring the lines between public and private and individual and collective transport, locally as well as globally. In 2016, transport network company systems, apps, private cars, services, drivers and passengers disrupted Curitiba's longstanding and well-regulated taxi system and market for licenses. In 2023, hailing a cab or a shared ride feels and costs the same for passengers (now customers). This study investigates whether these actors and technologies compete with or complement each other in this city, locating and quantifying the benefits for passengers of merging taxi and car ridesharing with the BRT system as first- and last-mile transport to and from BRT corridors. We developed mobile information and communication technologies and acquired, processed, and analyzed millions of data points for passenger location on BRT, ordinary bus, and taxi trips at the city scale. The shareability index for Curitiba's taxi or car rides was calculated, demonstrating that 60% of all taxi trips have the potential to serve as first- and last-mile transport solution to and from the BRT terminals, stations, and corridors and that nearly 40% of taxi trips both originate and end near (< 500 m) this BRT system infrastructure. By envisioning how transport network companies could merge into the built environment thanks to urban transport digitization, we have developed a model for integrating public transport with the analytic framework of transport network companies that could be deployed in other cities with similar challenges related to public transport, sociotechnical arrangements, system complexity, policy-making, and planning.

Extended author information available on the last page of the article

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Keywords Public transport integration · Bus rapid transit · Taxi · Car ridesharing · Ride-hailing · Trip chaining

1 Introduction

In urban transport systems, each mode of transport has its own rolling stock and often its own infrastructure, and must comply with specific national and local regulations. A city's mass public transport (PT) is frequently a large technological system that merges with other longstanding mass urban transport technologies, such as tram, train, subway, and bus rapid transit (BRT). These are at one end of the spectrum: their economic, social, and environmental costs per passenger are lower, but the service they provide is rigid in terms of space and time. At the other end, private cars and taxis offer much more flexibility in time and space but involve higher economic, social, and environmental costs per passenger. The pros and cons of each transport system are well known; the ability to go anywhere at any time makes cars very attractive for individuals commuting in large urban areas, despite their comparatively higher individual (internal) and social (external) costs. Over time it has become clear that most of these costs are paid with local public funds. The difference between the total external and internal costs generated by one passenger transported per kilometer via mass PT or a private five-seat car is staggering. Despite the significant local creativity that pioneered a BRT system in Curitiba, foreign influences and clear intentions to learn from other cities, transport modes, guidelines, legislation, techniques, and practices played a key role when this Brazilian city nurtured a PT innovation (Prestes et al. 2022).

In many cities, local transport policies were introduced to reduce car use, particularly during the 1970s when concerns about climate change began to emerge and a series of oil crises affected countries and continents over several decades. Since then, most national governments and policymakers have directly and indirectly subsidized fuel prices while an intense process of urban expansion resulted in metropolises where trip distance, congestion, and car fleet numbers grow steadily at a faster pace than the population (Mulley and Nelson 2020). In the evolution of large technological systems (Hughes 1987), current urban mobility arrangements also embody past policies, laws, social meanings, politics, culture, many other technologies, and contingency. At the core of contemporary mobility systems lie settled disputes between the actors that shaped the arrangement over time and competition between transport technologies. These large technological systems arguably acquire stability and inflexibility over time, and changes seldom occur—a tragedy of the commons seen in many cities around the world, which seems to suggest the need for new or complementary analytical frameworks for policymaking, planning, and the design of a sustainable PT (Richardson 2005).

Recently, information and communication technologies (ICT) have pervaded the human and nonhuman elements that comprise the fabric of cities: digitization and digital transformation. This sociotechnical change impacted urban mobility systems and networks and produced ride-hailing and ridesharing systems in which private cars function like taxis. These systems are also a new source of spatiotemporal data,

making it possible to analyze trip chaining using neural networks (Assemi et al. 2020). Digitization in urban mobility has blurred the spheres of public and private, individual and collective, and drivers and passengers; the software is free and urban dwellers' spatiotemporal data is the new gold (Medeiros et al. 2021).

This paper discusses spatiotemporal connections between the use of ordinary and ICT-based taxis and car ridesharing and the BRT system in Curitiba, southern Brazil. Taxis in this city were highly regulated by local and national governments until ride-hailing apps became widely used in 2016. In this article we investigate whether these systems compete or complement each other; our hypothesis is that ICT can foster integration between public and private urban transport systems, with transport network companies (TNC) and mobility-as-a-service (MaaS) apps optimizing unused transport capacity in four-seat passenger cars. If the BRT's feeder buses and taxis do not compete for passengers, PT and taxi and car passengers might share the economic benefits of an ICT-based integration of taxis, car ride-hailing, and the city's BRT system. In the sections below we present a brief overview of previous work on BRT, taxis, TNC, MaaS trip chaining, and the evidence of effects involving digitization and urban mobility. We discuss the shareability of car and taxi rides as a first-/last-mile solution for the BRT system, corridors, terminals, and stations.

2 Previous work

2.1 Merging ICT with urban mobility and contemporary sociotechnical changes involving cars, taxis, drivers, and passengers

Mobile ICT has arguably disrupted the sociotechnical arrangements of urban mobility. Shared ride services in North America have a local as well as global reach: Uber, Cabify, Didi Chuxing, and many other brands rapidly acquired a significant market in urban transport where taxis had always been exclusively regulated by public authorities (Shaheen and Cohen 2019). In 2017, the Chinese TNC Didi Chuxing acquired the Brazilian ride-hailing app 99 Taxi when it was widely used in Brazil's major cities exclusively for taxi ride-hailing. Locally, the company now markets its services under the brand 99 and offers ride-hailing in private cars or taxis on the same platform, with increasing price and level-of-service parity. Globally, the price per kilometer and user perceptions of both services are essentially the same, and Didi Chuxing is now one of the few TNC that are profitable in the global urban passenger transport market (Nguyen-Phuoc et al. 2020; Kharpal 2020). Amid these abrupt and rapid technological changes in cities from north to south, the concept of mobility-as-a-service (MaaS) emerged. Hensher et al. (2021) noted the continuing lack of agreement as to how MaaS should be defined, and the scarce evidence of its contributions to local policy sustainability goals, which are often part of urban transport plans.

Information and communication technologies have also merged with informal and self-regulated urban transport services like Jakarta's decades-old *ojek* motorcycle taxis. Following the widespread use of mobile ICT there, regulation and formalization of these services entered the transport policymaking agenda; in the past

this transport mode had been prohibited and targeted by law enforcement, and was considered "paratransit" by researchers and PT authorities. Today, several local *ojek* ride-hailing apps are part of the TNC business in Indonesia (Medeiros et al. 2018). Meanwhile, in Santiago, La Paz, and Mexico City rides in passing cars or vans along a fixed route with flexible stops and without the use of ICT (collective taxis) have been a longstanding practice since the 1980s (Figueroa 2001). These informal transport systems emerged when these cities were rapidly sprawling and no affordable, reliable public transportation alternatives (or sometimes no transport at all) were available for long-range trips connecting distant peripheral areas to the city centers (Figueroa 2005). In Santiago, this informal transport system became highly regulated. After the implementation of a BRT system in this city, collective taxi licenses are still issued to individuals that allow them to circulate along fixed routes, origins, final destinations, and city zones, maintaining the flexibility for passengers to embark and disembark at any location along the taxi route (Chile 2018).

On the other hand, cities with better access to mobile internet and higher per capita income recorded more ICT-enabled urban trips during the COVID-19 outbreak, while low-income groups in the same cities appeared to take fewer trips via this transport mode due to economic constraints (Rizki et al. 2023). Digitalization has also enabled multimodality in cities over the last decade, empowering individuals through a broader on-demand transport portfolio and apps that allow users to smoothly switch from one mode to another, in a combination of collective and individual transport modes and mapping (Shaheen and Cohen 2019). Even so, only a small share of commuting trips are intermodal in a metropolis like Berlin (Jarass and Oostendorp 2017). The configuration of the city mobility network was a significant factor in diminished traffic during the COVID-19 lockdowns, very briefly reducing delays and emissions in congested urban areas (Du et al. 2021).

Today TNC are proliferating around the world and defining prices for car or taxi rides, driver remuneration, performance rewards, and areas of service and supply through the hands of scattered private actors while remaining overlooked by most PT policymakers (Smith et al. 2018; Mukhtar-Landgren and Smith 2019). Furthermore, private TNC produces and holds all the spatiotemporal data on its users and trip supply/demand, data which might otherwise be available to third parties, like universities or PT or city planning authorities. But digitization in urban mobility has generated vast troves of data that also offer an opportunity to clearly understand use patterns for each urban mobility mode, thus permitting data-driven approaches and fostering urban mobility studies at an unprecedented scale. This has led to the age of digital data politics. The use and acquisition of data rely upon ownership, problem definition, and vested interests in the private sector, while the negative externalities of urban transport such as emissions, road crash injuries, and their various inequalities are solely handled by the public sector (Duarte and Álvarez 2019).

While the technological component in MaaS apps today is quite ordinary, the political component is not: branding, user databases, and records are precious resources. In 2016, TNC players snapped up large shares of the taxi ride market in Curitiba which prior to that time had been exclusively regulated by the local PT authority (the Curitiba Urban Development Company, URBS). This authority subsequently requested access to trip data from ride-hailing application companies for

planning purposes, and charged a city tax on TNC operations based on trip length. This data point value is provided by the TNC in an aggregated format, while disaggregated data of all trips made with TNC ride-hailing apps was not commissioned (Curitiba 2018). These emerging data sources are essential for urban mobility research, planning, and policymaking in Curitiba, a city that conducted its first urban travel survey in 2016 (IPPUC 2017). Mobility-as-a-service apps might also generate positive outcomes for sustainability of the local PT, such as reducing emissions originating in city mobility. A proactive approach led by the local government seems essential to championing MaaS (Hensher et al. 2021).

Taxi and car ride-hailing apps were a great novelty when they first emerged in Curitiba. Today, however, they operate amid well-defined boundaries and social groups: former and new taxi users, car owners, licensed taxi and car ride-hailing drivers, and local and global MaaS or TNC brands. Ride-hailing apps without a ride-sharing feature do not offer much more than the old, comfortable, well-established taxi services, which involve similar economic, environmental, and social costs as private car trips; it is just a better taxi, as Rayle et al. (2016) mentioned. In a data-driven study, Santi et al. (2014) measured the benefits of a taxi ridesharing model for passengers and drivers in New York that included taxi ride time, internal and external costs, fleet size, congestion, and emissions.

López et al. (2014) noted that taxi ridesharing has a rebound effect on sustainability: extra carbon emissions along with price reduction per passenger and a shift in transport mode from lower-emissions modalities (PT, walking, bicycling) to cheaper taxi and shared rides. This effect would be less alarming if the four-passenger car fleet deployed as taxis predominantly used natural gas, as they do in Rio and São Paulo (Adetax 2017), or if TNC or MaaS operations mostly involve electric vehicles, as seen in London (Bolt 2020) and Hamburg where a TNC launched fully shared electric-vehicle passenger-ride operations (Moia 2019). In Curitiba, ride-hailing apps only added ridesharing in 2020 to test a cheaper option for passengers. Over time this option was often unavailable during peak demand and in low-income regions, and did not involve lower prices for shared taxi or car rides. In fact, government-led policymaking and planning are necessary to drive positive changes in transport inequality and emissions trends.

In 2022, the Finish MaaS company Whim bought the Brazilian startup Quicko (with 500,000 registered users accumulated since 2018), along with the mobile app that offered most transport modes in the cities of São Paulo, Salvador, Curitiba, and Rio de Janeiro. This merge shut down operations in Brazil just six months later (Del Carmen 2022). It appears that MaaS currently faces an uncertain future involving a closer examination by policymakers and focusing on the potential sustainability outputs that this concept could bring to the urban transport sector (Hensher et al. 2021). In 2023 in Curitiba, a car ride with Uber costs on average 0.92 USD per kilometer (the authors 2023), while a taxi ride booked via a MaaS or a TNC app costs on average 0.96 USD per kilometer (CBN 2022), suggesting that today the prices and services are very similar.

Sundararajan (2016) dubbed the sharing economy crowd-based capitalism, in which people do not actually share resources (like empty seats in a car) but rather some people provide services to strangers in exchange for money. As *The Economist*

(2013) put it: "What's mine is yours, for a fee." But as cited above, sharing a car or taxi trip can reduce the number of circulating vehicles and optimize occupancy of five-seat cars; the average car occupancy in Brazil is 1.3 persons per five-seat vehicle (ANTP 2020).

Using data from 150 million taxi trips in New York, Santi et al. (2014) developed a network-based model that permitted optimal matching of shareable rides and demonstrated that cumulative trip length could be reduced by 40% with only a slight increase in passenger discomfort. Passenger discomfort is expressed in terms of the number of passengers on board, with an upper limit representing the delay incurred during individual trips from rerouting to pick up or drop off other passengers. These authors remarked that their model did not address passenger willingness to share a ride with a stranger, and called for future research on this aspect of the shareability model. In certain scenarios, the taxi system could be 40% more efficient and affordable or the fleet could be reduced by 40% in situations where 80% of taxi trips could be shared with minor differences compared to an individual taxi ride. This shareability model yielded an index that has recently been extended to quantify the benefits of ridesharing in other cities (San Francisco, Vienna, and Singapore), and in turn produced another model to predict the number of trips that could be shared, based on a few urban parameters (Tachet et al. 2017).

The ubiquitous nature of mobile ICT generates new, smarter transport systems that could potentially permit or partially replace PT operations with on-demand transport, incorporating spatial and temporal flexibility needed to transport passengers in smaller low-emission vehicles (Dowling and Simpson 2013; Kishii 2014; Winter et al. 2018). Sharing car and taxi trips reduces the internal and external costs of these trips, while the systemic effects of sharing in the social and environmental spheres have not yet been dimensioned through data-driven approaches, even in cases where the data is made available by TNC or MaaS companies (Clewlow and Mishra 2017; Wirasinghe et al. 2013).

Poó et al. (2018) published a longitudinal (1990–2015) literature review on working conditions and driver health in the global taxi industry, and emphasized the high internal costs paid by drivers with heavy workloads, lack of healthcare, and inadequate break time during daily shifts. Before the taxi sector merged with various TNC mobile apps that now involve private cars and "freelance" drivers, there were over 6,000 taxi drivers in Curitiba (URBS 2019); today they compete with more than 27,000 private car ride-share drivers (Marques 2020). The control of all taxi and car ride-hailing supply and demand by global and local companies generated constant criticism among the drivers, as did the variable share that the TNC takes from each taxi or ride price charged to passengers (up to 60% in Brazil). In response to these complaints, the São Paulo city government launched a public proprietary app called MobizapSP, which reduced this share to a fixed rate of 10.95% of trip cost; more than 20,000 drivers and cars registered with this platform within four weeks of its launch (Sao Paulo 2023).

When ICT merged with the established urban mobility sociotechnical ensemble, street demonstrations were seen across Brazil, and lobbying expanded in local and national parliaments, involving actors and social groups with vested interests (and assets) in taxi licenses and TNC and MaaS brands and platforms. Long, convoluted

legal battles followed, with some groups trying to keep regulation under the purview of local authorities (like public municipal transport) and others demanding changes to national labor legislation and loosening of local taxi regulations. Ultimately, the 1943 labor code was fundamentally altered (Brazil 2017) by eliminating employment ties between taxi license owners, TNC, MaaS companies, and the drivers and their cars.

2.2 Digitization in the trajectory of public and private TNC

Initially, research on ride-hailing applications mostly focused on comparing private car ride-hailing with taxis, stressing how the emergence of TNC rapidly transformed the taxi industry and how over time it became clear that private car-based ride-hailing drew people away from not only taxis but also PT (Feigon and Murphy 2016). Other researchers have investigated the relationships between these modes, systems, and networks, mostly relying on results of surveys conducted with PT, TNC, and taxi passengers (such as Voß et al. 2020; Rayle et al. 2016; Hawas et al. 2016). Most publications in the trip-chaining literature analyze one PT mode at a time, focusing on interchanges of passenger lines within train or bus systems, vehicle stop alighting, routing optimization, frequency, and vehicle occupancy (Adler and Ben-Akiva 1979; Primerano et al. 2008).

In a digital data-driven study, Jin et al. (2019) found that the TNC Uber complements and mostly competes with PT in New York during most hours of the day, even in areas with a good PT supply. But these authors also pointed out that it complements or offers an alternative to PT in situations when the latter is unreliable or offers a poor level of service. A similar investigation of the interaction between TNC trip origins and the location of bus stops in Pittsburgh found that this relationship was substitutional, supplementary, or not interactive (Grahn et al. 2021). In addition to these three types of interactions, this present case study discusses PT infrastructure and system integration with mobile ICT. One important factor is time; as the number of vehicles on mixed traffic roads has grown, congestion has increased and PT that utilizes its own traffic corridors has become faster than a car or taxi trip during peak hours. This is the case in Curitiba, where BRT passengers travel twice as quickly as those who ride ordinary bus lines in mixed traffic (Lindau et al. 2010; Deng and Nelson 2011).

Comparison of travel times for PT and private cars in cities that mostly rely on PT systems circulating within mixed traffic, as in Cape Town (Hitge and Vanderschuren 2015) and Dhaka (Gallagher 2017), reveals that PT takes significantly longer than private cars, highlighting the need for PT investments to move towards an integrated, multi-modal system that can compete with private car transport. A key improvement offered by BRT systems is the implementation of segregated, bus-dedicated lanes, which significantly improve the average operational speed, passenger convenience, and competitiveness of BRT systems over other urban transport modes (Hidalgo and Muñoz 2014; Deng and Nelson 2011). For example, in Klang Valley, an urban conglomeration in Malaysia, PT accounts for only 17% of the mode share, while 83% of daily trips involve private transport (Onn et al. 2014). Where PT

systems are integrated in terms of physical structure, network, systems, fares, information, and institutions, this share is much higher, as in Singapore and Hong Kong (Xie and Olszewski 2011).

Yet low-income PT passengers in Sweden pay relatively more to use PT than more affluent individuals, considering transport smart card users (Bondemark et al. 2021). In Dar es Salaam city, PT provides an excellent transport option, connecting homes, jobs, and private transport, substantially different from cities in the United States where public transport is less effective at connecting origins and destinations (Bwire and Zengo 2020).

Car or taxi ridesharing can be defined as prearranged, on-demand transportation services for compensation that connect drivers of private vehicles with passengers (Chan and Shaheen 2012). The potential for ridesharing to facilitate first- and last-mile PT connections in urban mobility, trip chaining, and mode transfer in the sharing economy has previously been studied by Shaheen and Chan (2016). Hensher and Reyes (2000) investigated trip chaining as a barrier to the tendency to use PT. But few studies have examined the potential optimization of unused passenger capacity in PT, taxis, and car rides through MaaS or TNC data, which is often privately controlled and poorly regulated by policymakers and public authorities. Within this context, this paper assesses the potential to optimize passenger transport in an individual, private mode (taxi) integrated with a collective public mode that has greater capacity and faster average speed during peak hours (URBS 2017) in Curitiba.

Curitiba's PT was launched in 1974 and utilizes BRT corridors where special high-capacity buses run on physically separate roads. Regular bus lines (feeder buses) running on regular roads with normal traffic connect to the BRT corridors at transfer terminals. The BRT system has been upgraded over the years with specially designed tube stations, geopositioning systems for the buses, and smart cards for fare collection.

Despite its relative success (after Curitiba's BRT concept was adopted in many other cities worldwide), the system faced challenges and lost 3.7% of its ridership between 2010 and 2014 and 18.9% between 2014 and 2018 (URBS 2017). One of the main challenges is growth: as neighboring cities attract people who cannot afford to live in Curitiba, almost 50% of regular bus passengers come from these surrounding areas (which have a population of 1.5 million, compared to the 2 million who live in Curitiba proper) and 35% of these passengers have daily commutes exceeding 2 h (COMEC 2008). Meanwhile, in its dedicated corridors, the BRT has headway as short as one minute and average operational speed of 20 km/h during peak hours, while the feeder buses have headways that reach 40 min and an average operational speed of 8 km/h (URBS 2020).

Curitiba's taxi system is regulated by URBS, the same body responsible for the BRT and feeder buses, which offers an advantage for integrating these two public/private modes. In fact, 64% of the 22 BRT transfer terminals have adjacent taxi stands (Duarte and Rojas 2012). Taxi licenses are emitted by URBS and involve regulations ranging from vehicle model and color to driver conduct and on-street taxi parking spots, which are found across the city and marked specifically in orange. Licensed taxis are allowed to transport passengers to the neighboring municipalities within the greater Curitiba metropolitan area, but not

bring passengers from them. The taxi fleet remained stable between 1975 and 2013, with a total of 2,252 vehicles (URBS 2019), while the population expanded approximately 200% to reach 1.8 million during these four decades (IBGE 2016). This means that the ratio of inhabitants per taxi jumped from 290 to 800 over this period; in comparison, the ratio in São Paulo in 2013 was 350 inhabitants per taxi and 196 in Rio de Janeiro. These numbers indicate the repressed demand for taxi services in Curitiba, and were calculated with the estimated population of São Paulo and Rio de Janeiro (IBGE 2018) and each municipality's taxi fleet in 2015 (ADETAX 2017). Additionally, the supply skyrocketed immediately when ride-sourcing companies started operations in the city in 2016 by simply transforming private cars into "better taxis" (Rayle et al. 2016) and incorporating car ride services into taxi-hailing apps (Reuters 2016). The city required TNC drivers to register with URBS, and more than 27,000 registered within four weeks of this requirement (URBS 2020), despite protests by taxi drivers demanding enforcement of TNC operations and drivers (Villa 2019). Curitiba's municipal tax revenues from TNC operations (U$ 8.4 million) eclipsed earnings from taxi licenses four-fold (Yano 2019).

Not only did the fleet remain the same over these four decades, but the technologies associated with taxi services also remained unchanged. Until 2013, there were two ways to obtain a taxi ride in Curitiba: by going to a taxi stand, most of which are concentrated in the central districts, or by calling one of the eight taxi associations, which communicated with their drivers via analog radio. But in 2014 two events began to challenge taxi operations in Curitiba: the emergence of apps for taxi ride-hailing, and private car ridesharing. As the number of taxi licenses remained steady for decades, their value skyrocketed up to US$ 80,000. Several licenses were often owned by the same person, who received daily fees from the drivers operating the taxis. Between 2007 and 2012, 15.5% of all taxi licenses changed hands (Bortolini 2012). The political power of taxi license owners was so strong that in 2012 the city council passed a municipal law supported by URBS that made it possible to inherit taxi licenses; this law was later overturned by federal courts, which ruled it unconstitutional (G1 2016). Between 2012 and 2017, licenses for Curitiba's four-passenger fleet reached a peak of 2,954 (URBS 2019).

In 2010 the number of cellphone lines in Brazil surpassed the total population (IBGE 2018), and in 2016 there were 0.9 mobile phones connected to the internet per capita (FGV-SP 2016). After decades of organizing taxi trips, radio taxi associations faced competition from taxi ride-hailing applications that were more attractive to both users and drivers. Users can hail a taxi more quickly and easily than calling a radio taxi association, see when their taxi will arrive in real time, as well as monitor the trip, while both drivers and users benefit from the partial removal of direct monetary transactions.

URBS initially stated that taxi ride-hailing applications did not comply with the 2006 municipal taxi regulations, and even threatened to suspend taxi licenses and fine drivers caught using them; perplexingly, the enforcement agents used the prohibited applications to hail taxis and identify these drivers (Al'Hanati 2014). But the user convenience, technological and innovative appeal of these mobile apps, and associated benefits to passengers and drivers led to widespread criticism of URBS,

which reconsidered its initial legal interpretation, leading to the broad use of taxi ride-hailing applications in Curitiba.

In 2016, private car ridesharing applications such as Uber and the local company T81 entered the market in Curitiba and added even more pressure on the taxi market, with Uber offering rides that were 50% cheaper than taxis on average (G1 2016), although these numbers have been contested; for example, Noulas et al. (2015) found that average Uber charges in New York were higher than yellow cab fares. Still, it did not take long for taxi ride-hailing application users to adopt ride-hailing applications and their fleets of ordinary cars: in 2016, a major player in Brazil, 99, merged its ride-hailing services based on private cars and licensed taxis, with advertising copy stating "a private car is a taxi in the new 99 app" and "99, where your mobility begins" (Moraes 2016). Bortolini (2012) found that taxis in Curitiba made an average of 18 trips each day, and in 2015 we found that this number was as low as 12, suggesting that the average daily number of licensed taxi trips has fallen since the arrival of this competition. In terms of national legislation, ride-hailing applications were considered private passenger transport and not subject to licensing by municipal transport authorities. Taxi drivers who used to rent taxi licenses on a daily or monthly basis migrated to private ride-hailing systems, avoiding bureaucratic constraints and working with their own cars and schedules. Private car ride-hailing applications began to operate in Curitiba in March 2016, and within a few months, an estimated 1,600 people were driving for Uber (Marchiori 2016).

There is a significant price difference between PT and taking a taxi in Curitiba: in June 2019, the transit fare was 1.2 USD (URBS 2019), while the taxi fare was 0.7 USD per kilometer plus a booking fee of 1.1 USD charged for every taxi ride (CBN 2022). As BRT ridership in Curitiba drops, taxi ridesharing could potentially offer a first-/last-mile solution for riders and bring BRT ridership up again. It is important to note that our intention is not to boost the number of taxi trips, but rather to make it possible to share existing trips. In other words, by assessing existing taxi trip origins and destinations we can infer how many of these trips started and ended near BRT transfer terminals and intermediate stations (tube stations). The formula proposed by Tachet et al. (2017) can then be used to assess the sharing potential for all taxi trips. This could lead to two benefits: increased BRT ridership by offering more people easier access to and from BRT transfer terminals and tube stations, and cheaper services in exchange for a slight increase in discomfort for single taxi passengers.

3 Data and methods

All values in Brazilian Reais were converted into US Dollars using the average exchange rate for the month and year of the citation listed by the Central Bank of Brazil (CBB 2023). Socioeconomic and demographic data for 23,965 census tracts and GIS files were obtained from the Brazilian Institute of Geography and Statistics (IBGE 2018) and Curitiba's Institute for Research and Urban Planning (IPPUC 2017) and compiled. Trips using PT in Curitiba were further differentiated according to whether they used BRT or feeder buses. Most feeder bus lines have physical and

fare integration with the BRT system at the 18 BRT transfer terminals, which are also bus transport hubs located along dedicated BRT corridors. (Fig. 1) Most tube stations, which are not located directly in BRT terminals, are also positioned near these BRT corridors, mostly in ordinary bus terminals, and connect to the BRT systems in non-stop direct lines between transfer terminals. Fares are collected before boarding in the transfer terminals and tube stations, providing direct geolocations of trip origin. For feeder buses, we developed a script to match a smart card log with the closest geolocation of feeder buses. Non-stop bus lines that run mostly outside the segregated BRT corridors but use the tube stations (known as Direct Lines) were also considered part of the BRT system, since they directly connect to BRT transfer terminals, make four times fewer stops than the feeder buses, and utilize BRT corridors in parts of their routes. Passenger transfers from feeder or Direct Line buses in BRT or bus terminals do not require another transport smart card swipe, so their origin or demand location was attributed only once, at the check-in location of the transport smart card readers.

The taxi data comprised 8,050,748 taxi trips booked via the taxi ride-hailing application 99 throughout 2015. This dataset includes unique identification numbers for 1,885 taxis as well as geolocations and timestamps for the origins and destinations of each trip. For BRT and regular bus data, we used the passengers' anonymized smartcard data acquired from URBS's web services, for each data point adding a geolocation stamp sourced in the GPS installed on buses or the geolocation of the static smartcard reader installed in BRT terminals and stations. We gathered one day of data in 2015 and ten days in 2016 (including both workdays and weekend

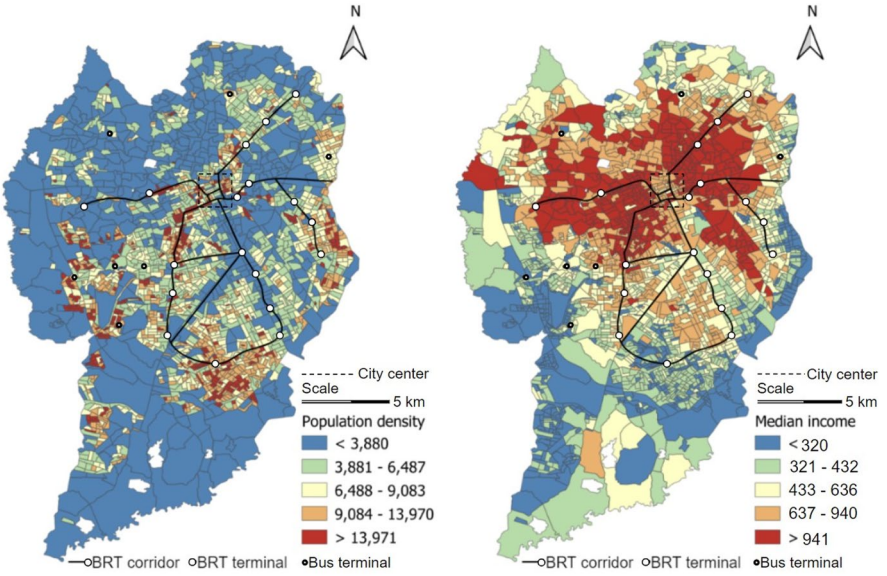

Fig. 1 Population density (number of inhabitants per km^2) in census tracts (left) and spatial distribution of median household income (USD per inhabitant) per census tract in Curitiba (right). GIS visualization by the authors. Data source: IBGE (2016)

days), totaling 3,273,876 bus trips; note that these days did not fall into periods of the year when average ridership significantly decreases due to holidays or school vacations (URBS 2020). This average bus ridership significantly differs on weekdays and weekends, while no significant average ridership changes are seen from year to year, with the exception of the years after the COVID-19 lockdowns (URBS 2020). We observed a 94% re-incidence rate for the smartcards used to access the bus system in 2015 and in 2016. Curitiba's shareability index was calculated according to the work of Tachet et al. (2017), which predicts the potential for ridesharing in cities with more than one million inhabitants. The average traffic speed in Curitiba was obtained by running a script on the TomTom company website via web service for a period of seven consecutive days.

4 Results and discussion

In 2015 Curitiba had an extremely inadequate taxi fleet of roughly 3,000 four-seat passenger cars to serve a growing population of 1.8 million inhabitants. None had ICT mobile applications to hail, book, pay, or share a taxi ride. At that time, these cars were required to be no more than five years old and have a customized orange paint job and a city-issued license and plate. No TNC or MaaS providers operated in the city until early 2016, when passengers merged the meanings of taxi and car ride-hailing through the widespread use of taxi and private car ride-hailing apps across the city that simultaneously offered both services. Over time, passengers came to merge the image of these transport modes. The highly regulated and unbalanced taxi system in Curitiba, with major gaps between demand and supply, became a free market for urban transport at the hands of many TNC. In 2022, more than 30,000 drivers were at the wheels of four-seat passenger cars for hire, in either orange taxis or TNC fleets. Drivers now can buy, lease, or rent cars and register simultaneously with a myriad of TNC applications, and the cars no longer need to be orange. Curitiba had 500 fewer taxis in 2020 than in 2015 (URBS 2020).

To discuss our results against the backdrop of the literature cited, we assumed that taxi rides taken in 2015 using the 99 app were representative (or at least a proxy) of the total taxi and TNC rides currently taken in Curitiba. This was also a methodological choice by the authors to circumvent the current lack of disaggregated data commissioned from TNC or MaaS apps for data-driven academic studies like ours or by the Curitiba planning authorities (Curitiba 2018).

In 1965, the city of Curitiba proposed a master plan to face rapid growth that combined land use, PT, and a roadway system for mixed traffic running in parallel to dedicated bus corridors. Today these corridors are still exclusive for the use of the BRT fleet, with exceptions only for emergency and police vehicles. The plan involved five main mass transport lines (see the BRT corridors in Fig. 1) intended to structure the city's future development and permit the implementation of a BRT system on a city-wide scale. Four-lane avenues for rapid car traffic were built one block parallel to these main lines. High-density and verticalized zones were only permitted along these lines (or PT corridors and rapid avenues) for two reasons: high-density areas would provide passengers for the PT system, while a good system

would attract inhabitants to these areas. While various improvements were made between 1965 and 2015, no significant changes to the quantity or spatial distribution of the BRT infrastructure (fleet, terminals, tube stations, and corridors occurred between 2015 and 2020 (URBS 2009, 2020), reinforcing the validity of the data collected. Additionally, there were no significant changes in the fleet, routes, timetable, or average number of weekday and weekend passengers during the same period and before the start of COVID-19 lockdowns in March 2020.

In fact, verticalization along the corridors attracted middle-class residents eager to live in high-rise buildings (which are considered safer than houses, an important factor where crime rates are high) but who prefer cars to BRT. In fact, Curitiba has one of the highest motorization rates in Brazil, with 0.68 motorized vehicles per inhabitant, compared to 0.56 in São Paulo, for instance. Meanwhile, the surrounding cities have attracted people who cannot afford to live in Curitiba but use its transport system to commute to work every day; areas with lower density (shown in blue in Fig. 1) are served with regular (non-BRT) buses. In 2014, the local transport authority introduced smartcard-only policy to the smaller buses to address low occupancy rates during off-peak hours in an attempt to reduce operating costs, which ultimately impact user fares (URBS 2014). These buses have roughly half the capacity of feeders, and passengers must pay fares with a transport smart card (cash is not accepted); they run in lower-density areas of the city (see Fig. 1) and do not allow passengers to change to the feeder buses or the BRT system without paying an additional fare (URBS 2009). This suggests that even smaller vehicles (like taxis) could serve these areas during specific periods with ridesharing schemes.

As we can see in Fig. 1, which depicts population density and median income distribution according to Curitiba's census tracts and the BRT corridors, the population density is indeed higher along the corridors. However, it is also clear that higher-income households live in Curitiba's central areas where most of the BRT corridors and transfer terminals are concentrated.

To determine whether taxi and regular bus systems compete or could complement each other, we first analyzed aggregated temporal and spatial data on their usage during weekdays (Monday to Friday). Because the data for the regular bus system only indicates where people boarded (i.e., tapped in) and not where they got off (since passengers do not have to tap out when alighting), we aggregated origins of trips taken with PT and origins of taxi trips by one-hour time periods. To be able to compare the demand in these two systems, each system's demand peak was normalized to 1; as this normalized data in Fig. 2 indicates, the demand for regular buses (that feed the BRT system) is high during the morning peak hours, while taxi demand peaks in the late morning with less pronounced valleys during the day and evening peaks, and finally decreases less abruptly during the evening.

In order to understand how spatial demand for both systems changes over time, we plotted the demand for taxis and regular buses aggregated by census tract for morning and evening peak hours (see Figs. 3, 4): Fig. 3 shows the distribution of bus and taxi origins during morning peak hours (6 a.m.–9 a.m.), which were determined from Fig. 2, while Fig. 4 depicts evening peak hours (4 p.m.–7 p.m.). These figures show that taxi origins are mainly concentrated in the urban center during both morning and evening peak hours, with some branching following the BRT corridors. The

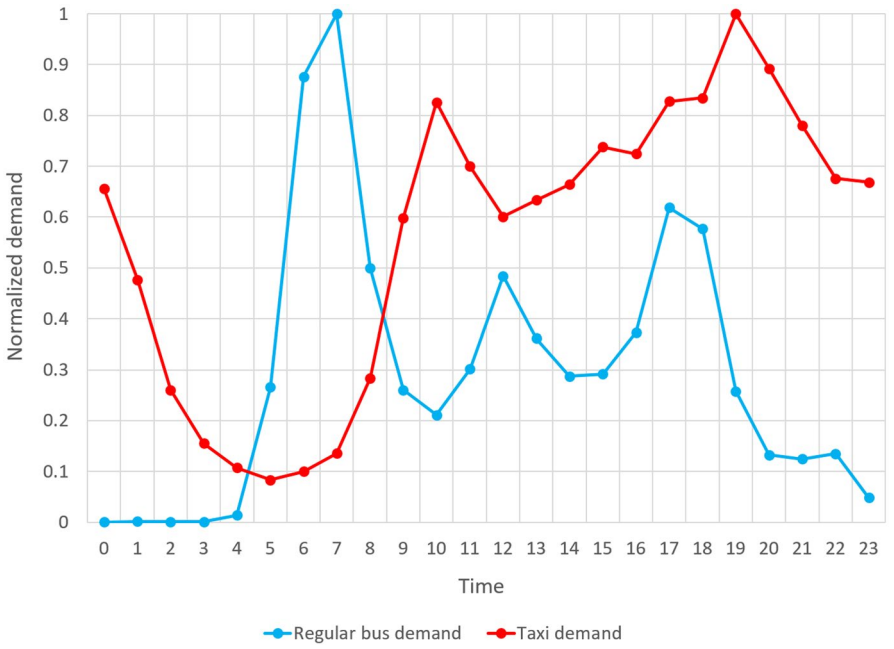

Fig. 2 Hourly variation in total demand for regular buses and taxis

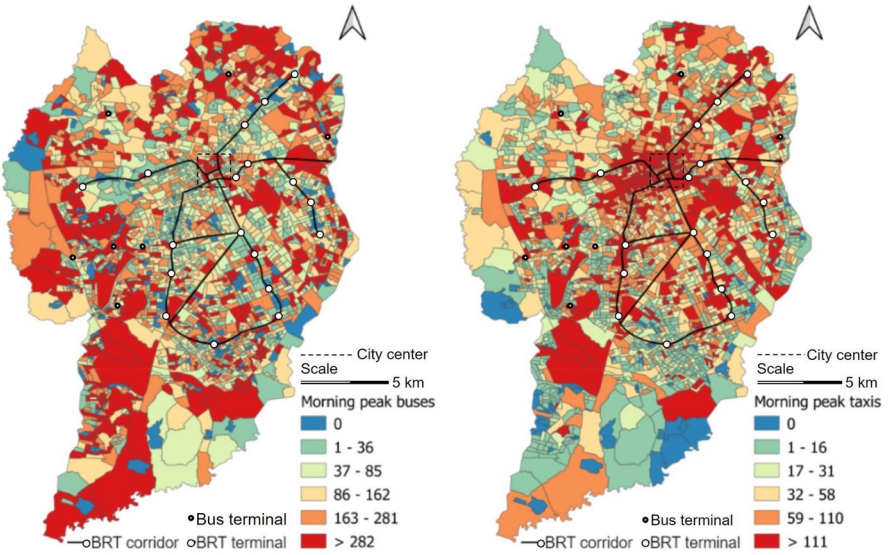

Fig. 3 Distribution of feeder/regular bus origins (left) and taxi origins (right) per census tract on weekdays during morning peak hours. Data source: URBS and 99Taxi

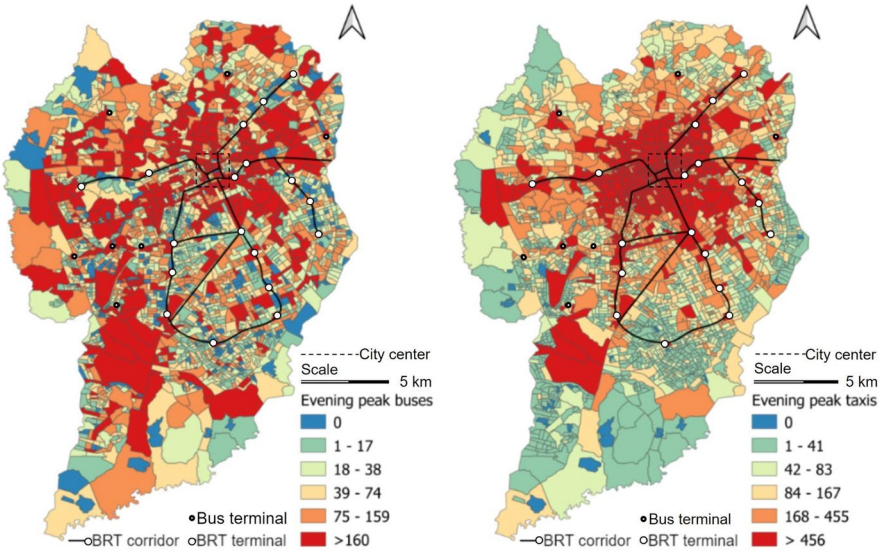

Fig. 4 Distribution of feeder/regular bus origins (left) and taxi origins (right) per census tract on weekdays during evening peak hours. Data source: URBS and 99Taxi, 2016

average parallel distance between BRT corridors seen in Figs. 3 and 4 is 4.2 km. On the other hand, during the morning peak hours, demand for regular buses that run outside the BRT corridors is spread throughout the city, with major concentrations in the peripheral areas, a phenomenon not seen in taxi rides (Fig. 3). As depicted in Fig. 4, the effect is different in the evening, with most regular bus trip origins concentrated in the central part of the city. Since Curitiba's system centers around a trunk-feeder system, demand for PT in the morning tends to originate in regular bus stations in the peripheral areas that feed the BRT in the transfer terminals. Because of the way both systems are integrated physically and in terms of fares, passengers that move from regular buses to BRT at transfer terminals do not count as demand.

The purpose of the bus trips was to commute between home and work for 88.9% of the passengers, while 2.9% of the passengers commuted between their home and school, and 8.2% of the passengers had other purposes (COMEC 2008). Among these same surveyed passengers, 42.9% had the city center as their origin or destination (see Figs. 3, 4), 32.7% declared having a car in their household, and 74.4% of the bus passengers described the transport system as terrible, bad, or average. For all transport modes, 53% of households owned at least 1 car (0.4 cars per inhabitant in Curitiba), the final destination of the trip was home for 47%, the workplace for 21%, school for 18%, 68% reported living or working in the city center, and 14% declared other trip purposes (IPPUC 2017).

We also analyzed the aggregated spatial correlation between taxi and regular bus trip origins. The spatial correlation coefficient is calculated as the ratio of the total number of trips originating in a particular census tract, using Spearman's rank correlation to detect trends as described in Gauthier (2001). The resulting R

coefficient between demand (i.e., trip origin) for regular buses and taxis is 0.34, indicating that the spatial correlation between the two analyzed transport modes is weak.

The temporal and spatial patterns for regular buses and taxis clearly indicated a distinct demand, suggesting the use by different population segments and/or for different purposes. This also led us to conclude that these two transport systems are not competing with each other, encouraging us to investigate other prerequisites for using taxi ridesharing as a first-/last-mile solution to and from BRT and potentially helping to recover BRT ridership. To do so, we calculated the percentage of existing taxi rides that originated or terminated near BRT transfer terminals and tube stations.

We found that approximately 60% of all taxi trips originated within 500 m of a BRT transfer terminal or tube station; similarly, 60% of all taxi trips ended in this same 500 m zone. The regular bus system is intended precisely to bring passengers to and from the BRT system, and as a result these individual taxi trips could potentially be shared. Even though we cannot claim that the existing taxi rides served as first- or last-mile solutions, we can use the taxi shareability formula developed by Tachet et al. (2017) to determine the potential for taxi ride sharing: regardless of the initial purpose of a taxi trip, the remaining free seats in the taxi could be used for up to three additional passengers as their first-/last-mile solution to or from a BRT transfer terminal or tube station.

The taxi shareability formula (Tachet et al. 2017) evaluates the fraction s of taxi trips that can be shared as follows: $s = 1 - (1/(2L^3))(1 - (e^{-L})(1 - (1+2L)e^{-2L})$, where L is a dimensionless quantity that depends on the density of trip demand, the shareability delay Δ, average traffic speed, and the city area. Shareability delay Δ refers to the fact that when rides are shared, a certain detour is typically incurred; this shareability delay imposes an upper limit on the implied delay, which was set to 5 min in this study, as suggested in Santi et al. (2014). The other parameters were defined for Curitiba as follows: the city area is 435 km^2, the average speed is 32.2 km/h, and the taxi trip density is 919 trips per hour. This yielded a shareability index of 0.87 - assuming that all customers are willing to share rides - which approaches the indexes found in cities such as San Francisco, Singapore, and New York (Tachet et al. 2017) and indicates that most taxi trips could be shared without significant time delays, even though this sharing is not currently offered in the city.

The shareability analysis highlighted the potential benefits of taxi ridesharing, which as of this writing have only been estimated for cities with high per-capita incomes and could also be applied to large cities in middle-income countries; this is particularly encouraging considering that the vast majority of urban population growth is expected to take place in these countries. The results also suggest that combining and better integrating PT and taxis could reduce traffic even more effectively if ridesharing is implemented systematically. The potential impact of policies to encourage sharing is also clear from Fig. 5: for instance, if an incentive policy is implemented and boosts the percentage of taxi customers willing to share a ride from 20 to 40%, the resulting portion of shareable rides (interpreted as the probability of finding another customer willing to share a ride) would increase from about 30% to over 60%. This increase would result in a better customer experience (in

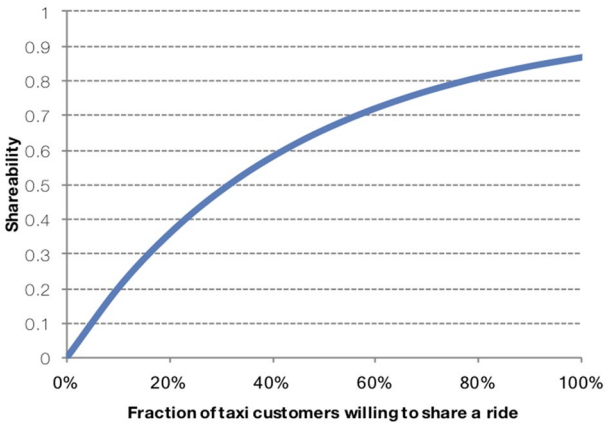

Fig. 5 Fraction of shareable taxi rides, as a function of the percentage of taxi customers willing to share a ride

other words, a higher likelihood of actually sharing a ride), which in turn could initiate a positive feedback loop and augment the effect of incentive policies.

In addition to the 60% of existing taxi trips that could potentially serve as BRT feeders, we also found that the starting and ending points of roughly 40% of the taxi trips were within 500 m of a BRT transfer terminal or tube station. As such, these trips could be shared with passengers who usually take BRT, serving as first- and last-mile intermodal trip chaining. Since taxis and car ride-hailing are expensive modes of transport, low-income passengers are less likely to use them, but they become more affordable when trips are shared. Moreover, during peak hours Curitiba's BRT in dedicated corridors reaches higher average speeds than mixed traffic that includes regular and feeder buses as well as taxis. The city could encourage taxi sharing in some regions by allowing shared taxis to utilize BRT corridors when carrying more than one passenger to benefit from these faster speeds.

Our results indicate that a taxi ridesharing system integrated with the BRT system developed and incentivized by local transit authorities could potentially be successful. However, it took private car and taxi ride-hailing applications more than five years into their operations to offer a ridesharing feature. Several months later, this ridesharing option in private car and taxi ride-hailing applications was often unavailable. We found the average Euclidean distance between the taxi trip origin and destination was 4.5 km; using this distance as a proxy for the trips currently served with TNC, we estimate that more than 240 million trip kilometers served by these companies have unused passenger capacity. Figure 6 illustrates our integration concept based on a shareability model which could include not only the taxi fleet but also the private cars used in ride-hailing apps that currently offer the same service as taxis in the city. In our system, drivers in individual trip mode with a destination or route passing within up to 500 m of a BRT transfer terminal or tube station could switch to taxi ridesharing mode and serve more than one passenger. In Fig. 6, A represents the point of origin for taxi or private car trips, while B, C, and

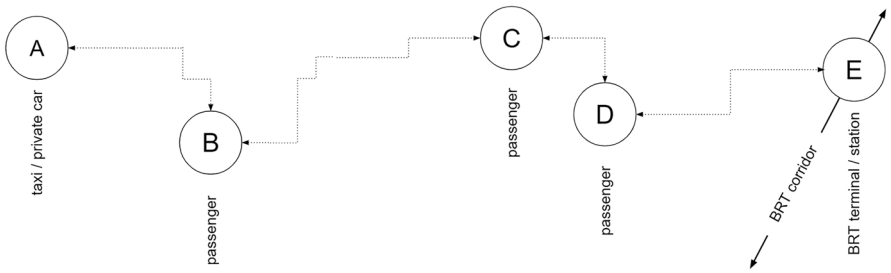

Fig. 6 Trip-chaining diagram for passengers in cars or taxis, as a first- and last mile transport service from and to a location along a BRT corridor. *Source*: The authors, based on Santi et al. (2014)

D are the spatiotemporal locations of regular (or BRT feeder) bus trip origins; E is the spatial location of the closest BRT transfer terminal or tube station to point D, where passengers on this taxi or private car shared ride would transfer from and to the BRT system. The maximum length between A and E is 8 km, resulting in a trip of roughly 15 min, considering an average speed of 32 km/h.

5 Conclusion

The BRT system in Curitiba is operated by three private corporate consortiums that operate in three different areas of the city; all ticket revenue is controlled by the municipality, and the system involves rigid timetables, technologies, routes, stops, and vehicle types defined in the public bid process. The concession holders are subsequently remunerated by operational kilometer and vehicle type (URBS 2009). This clearly represents a challenge for planning authorities in drafting the call for bids as well as monitoring and adapting operations over time (Arbex et al. 2021), and when responding to variations in demand or even contingencies, such as the coronavirus pandemic and how it impacted traffic system delay (Du et al. 2021). With the next public tender for PT operations in Curitiba expected in 2025 (URBS 2009), we suggest that the PT authorities design a call for bids that considers a broader view of PT systems, network integration, and car ridesharing. In this study we geolocated and estimated the potential shared benefits of TNC merging with PT, made possible through the ubiquitous and mobile ICT that could foster significant changes in PT policymaking, planning, and operation. It appears that one system could monitor costs, planning, ticketing, intermodal transfers, and trip chaining in contemporary PT. Furthermore, the design of the BRT terminals, tube stations, and fare portfolios could be assessed and potentially revised by combining mystery shopper-type passenger surveys as discussed in Voß et al. (2020), in combination with data on city transport smartcard use frequency, location, and passenger profile. It is important to mention that the current constructed PT infrastructure was designed and implemented three decades ago, and that passenger inconvenience and the negative image of PT must be identified and addressed, since these factors are extremely important to the perception, attractiveness, and convenience of Curitiba's PT system.

The high shareability index (0.87) found in this study creates an opportunity to plan this integration of public and private transportation. The analytical framework we created by envisioning this novel integration of mobility modes within the existing sociotechnical ensemble of urban mobility and stressing the opportunities offered by digitalization could be applied to other cities with BRT systems; this would immediately boost the attractiveness of these BRT systems by transferring riders to feeder (ordinary) buses with the convenience of a car or taxi trip. We do, however, acknowledge that political, economic, and regulatory factors are part of the equation despite such promising results, and most likely present the most complex obstacles. Still, developing customized digital systems to manage PT costs dramatically less than it did a decade ago, especially considering the economic scale of this market and the potential for external cost reduction that ICT offers. Ultimately, our findings backed the hypothesis that regular buses and taxis do not share the same public, indicating that both PT and taxi users could benefit from ICT-based integration.

To this end, our study offers strong evidence that even with limited resources it is possible to develop digital tools to collect vast troves of data at the city scale using existing sensors, systems, and databases. New applications are virtually limitless, and Curitiba's pioneering BRT could get the technology update it needs, including barrier-free fare collection, digital ticketing, flexibility, and on-demand supply, which are some of the requirements for better performance of urban PT systems and services (Winter et al. 2018). Access to longitudinal, anonymized, and disaggregated data on taxi and bus trips has enabled and shaped our analytical framework, as it and the TNC and MaaS operational data will be essential to the future of mobility in Curitiba and in any other cities that wish to avoid the familiar trajectory of falling PT ridership and declining attractiveness of public systems while car use and congestion increase.

One limitation of our study is the assumption that taxi rides in 2015 are representative of or proxy for current taxi and car ride-hailing ride numbers. For this reason, public authorities should incorporate anonymized data from TNC and MaaS operations within Curitiba into regulatory instruments, along with data commissioned for planning and academic research purposes, as discussed in Medeiros et al. (2022). Given the actual market size, competition, and strategic value of spatiotemporal data in operation planning and design and the dispute for passengers, private companies rarely or only occasionally commission data (as the TNC 99 did for this study in the past). Another limitation is that our analytical framework for transport integration involving mobile ICT better fits cities (or their parts) in which most of the built PT infrastructure derives from long-term application of the TOD planning concept and those where PT is predominantly supplied by buses, as in the case of Curitiba and its comparatively large scale BRT-exclusive corridors.

Future studies might investigate and call attention to (1) the current perceived image and comparisons between PT, taxis, and car ride-hailing to complement or further discuss the findings of our study; (2) the deployment of our analytical framework in studies of cities well served by a subway or other PT modes that operate in segregated lanes separate from mixed road traffic; (3) the willingness of passengers to share taxi or car rides with transfer to BRT with economic benefits in total price and shorter trip times, as well as impacts on image perception among bus passengers, if the Curitiba BRT system substituted feeder or regular buses with shared

taxi or car rides; and (4) the potential rebound effect that ridesharing might have on emissions and transport sustainability when TNC and MaaS fleets are mostly composed of vehicles that use fossil fuels, as discussed in López et al. (2014).

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Data availability Data is available for academic use or use by Curitiba's public authorities upon request to the corresponding author and approval by the data commissioners cited in the materials section of this manuscript.

Declarations

Conflict of interest The authors declare no conflict of interest and compliance with ethical standards as requested in the submission guidelines of the publisher, Springer Nature.

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Authors and Affiliations

Rafael Milani Medeiros[1] · Fábio Duarte[2] · Iva Bojic[3] · Yang Xu[4] · Paolo Santi[2] · Carlo Ratti[2]

✉ Rafael Milani Medeiros
rafael.medeiros@hcu-hamburg.de

Fábio Duarte
fduarte@mit.edu

Iva Bojic
ivabojic@mit.edu

Yang Xu
yang.ls.xu@polyu.edu.hk

Paolo Santi
psanti@mit.edu

Carlo Ratti
ratti@mit.edu

[1] HafenCity University for the Built Environment and Metropolitan Development, Hamburg, Germany

[2] Senseable City Laboratory, Massachusetts Institute of Technology, Cambridge, USA

[3] SMART, Massachusetts Institute of Technology, Singapore, Singapore

[4] Land Surveying and Geo-informatics, The Hong Kong Polytechnic University, Hong Kong, China