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Mobility-as-a-Service and the role of multimodality in the sustainability of urban mobility in developing and developed countries

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ABSTRACT

Mobility as a service (MaaS) is an emerging framework that integrates multiple transport services into a single and intuitive platform. This paper contrasts the urban passenger transport markets in developed versus developing economies to understand the challenges of integrating mobility services using the MaaS framework, with a focus on decarbonization and sustainability as societal goals. In addition, we conducted a Life Cycle Assessment of carbon emissions and energy requirements of travel alternatives in the city of Santiago, Chile, to shed light on the effects of multimodality as an environmental tool. A summary of findings follows. Data sharing and open data are new in developing countries, and thus more investment in data infrastructure is required so that MaaS can leverage digital technology and network optimization. If the scalability of MaaS is an open question in developed countries, it is more so in developing countries, owning to institutional and financial constraints that are present in the latter. The lack of public subsidies to support formal public transport is a key limitation for the implementation of MaaS schemes and multimodal frameworks in the developing world. Regarding formality, in countries with an informal public transport sector, a potential implementation of MaaS will be spatially constrained to those locations where public transport operates formally and frequently (BRT and rail lines), limiting its spatial coverage and posing social equity issues. In countries with scarce or no public funds available for the transport sector, MaaS could be used as a catalyst for a broad environmental and equity-seeking transport pricing reform which requires a direct involvement of public sector in both regulation and financial backing. We conclude that the formalization and general improvement of the public transport sector, the regulation of shared-mobility platforms including the formalization of the work of drivers, and the setting of proper pricing and subsidization instruments in the direction of internalizing the social costs of motorized traffic, are all prerequisites for any MaaS system that aims to improve economic efficiency, social equity, and sustainability.

1. Introduction

Transport shapes contemporary life by providing people mobility services to access activities. People, on the one hand, enjoy the benefits of mobility, and on the other hand, endure the external costs of traffic, including traffic crashes, congestion, pollution and noise. Air pollution from mobile sources is responsible for ill health and premature deaths, crop losses and negative impacts on ecosystems (Becker et al., 2012; Korzhenevych et al., 2014). Concerning global warming, the long-term temperature effect from current emissions is mostly determined by CO_2, and fossil fuel combustion for the energy, industry and transport sectors are the largest contributors on a 100-year period (IPCC, 2021). The transport sector account for 23% of the global energy-related CO_2 emissions; transport-related greenhouse gas emissions have doubled between 1970 and 2010 and 80% of that emission increase has come from road vehicles (Sims et al., 2014). Therefore, a shift towards low-carbon mobility can indeed have a significant effect on reducing carbon emissions, which is a necessary step to reduce global warming in the next decades, under the current scenario of widespread and intensifying climate change (IPCC, 2021).

It has long been established that the transport market cannot by itself reach an efficient equilibrium in the presence of negative externalities, calling for action from the government to correct this market failure (Santos et al., 2010). Sustainable transport policies should be aimed to

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create a balanced transport system, which provides convenient walking, cycling, and public transport alternatives without neglecting the car (Buehler et al., 2017). In this paper, we analyze how Mobility as a Service (MaaS) can move us closer or further away from the objective of decarbonizing transport, paying attention to the peculiarities of the transport systems in developing and developed countries.

While the concept of MaaS was coined more than a decade ago, until now there exists no consensus definition of MaaS. This is despite several attempts to clarify what MaaS is and what is not (Hensher et al., 2021b) and a few trials and commercial offers of MaaS in the developed world (see Hensher et al., 2020). However, common elements of usual MaaS definitions refer to MaaS as a multimodal user-centric mobility management system, in which an integrator combines several travel alternatives through a single digital platform that features trip planning, booking, ticketing, and payment (Hensher et al., 2021b; Kamargianni et al., 2018). Authors sometimes add that MaaS is more than a digital trip planner, that it could work in different spatial scales (local, metropolitan, regional) and pursue sustainable transport policy goals (Hensher et al., 2021b).

In the developing world, the concept of MaaS seems to be even more abstract and challenging to implement because so far the MaaS progress has happened in developed countries whose transport markets differ remarkably from those in developing countries, where the markets usually are unstructured, informal and sometimes poorly regulated (Dzisi et al., 2022). This includes the situation of new mobility technologies such as ridesourcing,[1] as in developing countries ridesourcing drivers sometimes work unregulated in a grey legal arena (Fielbaum and Tirachini, 2021; Fielbaum et al., 2023). Regardless of the fundamental differences in the transport market observed between developed and developing countries, MaaS has always been promoted as a multimodal solution aiming to reduce private car use and its negative consequences (such as traffic congestion and emissions) as well as improve public transport ridership by, for example, using on-demand transport services such micro-mobility, ride-sharing, and ridesourcing services to address the first- and last-mile issue associated with public transport use. Whether these aims are to be reached crucially depend on the design of the MaaS schemes to be implemented.

In this paper, we analyze the societal value proposition of MaaS, with a focus on the differences between developed and developing countries that are relevant for the setting and the sustainability outputs of MaaS, particularly regarding environmental and social effects. We pay particular attention to decarbonization potential of MaaS within the transport sector.[2] We first review the importance of multimodality, particularly in the presence of new mobility platforms enabled by Information and Communication Technologies (ICT), including issues on financial backing, data sharing and governance. Second, we analyze the transport sector in developing countries to highlight how they differ from those in developed countries, with a focus on elements that may interfere in the development of successful MaaS schemes. The relationship of MaaS and social equity that is pertinent in developing countries is also examined. Third, we review how MaaS can be used to pursue decarbonization purposes, with reference to the latest research findings that provide insights into how future schemes should be designed. Fourth, we develop our own estimation of carbon emissions and energy requirements of different travel modes (per passenger kilometer) for the city of Santiago, Chile, to illustrate the influence of different vehicle technologies (internal combustion engine or electric) and service types (personal use, shared vehicles or share rides/public transport). This exercise is used to compare results to similar research efforts from developed countries. Finally, we conclude with a reflection about MaaS issues that need to be resolved for MaaS to be a viable, scalable, green and well-functioning user-centric mobility framework in developing countries. Some of these issues are hard to solve, which makes the applicability of MaaS principles much harder in developing than in developed countries.

2. Multimodality and MaaS

2.1. Modal efficiency and the need for integration

Powered by digital technologies, a number of mobility services such as ridesourcing, ride-sharing, bike-sharing, micro-transit have recently emerged, providing travelers with new ways of accessing and using shared vehicles. How these new services might complement or compete with traditional modes – particularly the private car and fixed-route public transport – is a hot research topic with relevant public policy implications (Veeneman, 2019; Tirachini, 2020). From a sustainability point of view, the least desirable outcome would be that mass public transport services are replaced by personalized point-to-point motorized mobility services in large numbers, which brings challenges to the decarbonization objectives of passenger mobility. It is noted that in some situations where public transport level of services is poor (e.g., rural setting, late night), using on-demand door-to-door low-occupancy motorized vehicles to serve the demand could be more efficient than using conventional public transport. Thus, it is important to understand the efficiency of these new mobility services and appropriately position them in the mobility landscape, such that MaaS could be used as a framework to leverage the merits of different transport modes through integration. Integrated systems not only provide improved services to individual travelers but also may help the society achieve sustainability through, for example, reducing energy consumption and greenhouse gas emissions, if proper incentives are provided.

For the aforementioned reasons, cities need a multimodal future to deliver MaaS promises. The modal efficiency framework developed by Wong et al. (2020) is useful for understanding this premise, as all modes of transport can be positioned along a 2-dimensional scale that represents their spatial and temporal efficiency. *Spatial efficiency* is determined by the number of passengers carried per unit area. *Temporal efficiency* represents the proportion of time the vehicle is on the road serving passengers. Modes can be largely classified into four quadrants as shown in Fig. 1, with the relative positions of different modes within each quadrant based on their spatial efficiency and temporal efficiency. For example, the private car is placed in the third quadrant because *on average* it spends less than 5% of its life serving customers (i.e., low temporal efficiency) and when it does, the level of occupancy is low, with an average of 1.2–1.5 passengers per vehicle (i.e., low spatial efficiency) (see, for example, Hensher et al., 2020). By contrast, the public transport modes are the most efficient, both spatially and temporally, because they can transport many passengers per vehicle (hence the term mass transit) and each vehicle typically has a busy schedule/timetable to follow (i.e., high temporal efficiency). The use of these highly efficient modes, however, requires an access/egress component that is presently dominant by walking and cycling modes, collectively referred to as active modes. The active modes are very efficient *spatially* (because these modes require little space) but not so *temporally* due to their limited use for long-distance travel. The opposite is true for shared modes such as ridesourcing and ride-sharing which typically have a low occupancy but a high usage level (i.e., spend most time serving passengers). Ideally, the shared modes should complement public transport and active modes because shared modes, either operated under a fleet-managed or a peer-to-peer model, are temporally efficient but spatially inefficient due to low occupancy. The environmental assessment of Section 5 quantifies this issue. The real concern, however, is that the opposite might occur in some market segments where shared modes replace public transport in its entirety (i.e., point-to-point travel) and/or its first-and-last-mile

[1] Ridesourcing is understood in this paper as "prearranged and on-demand transportation services for compensation in which drivers and passengers connect via digital applications" (SAE International 2021).

[2] For a list of review papers that focus on other MaaS related topics, see Butler et al. (2021).

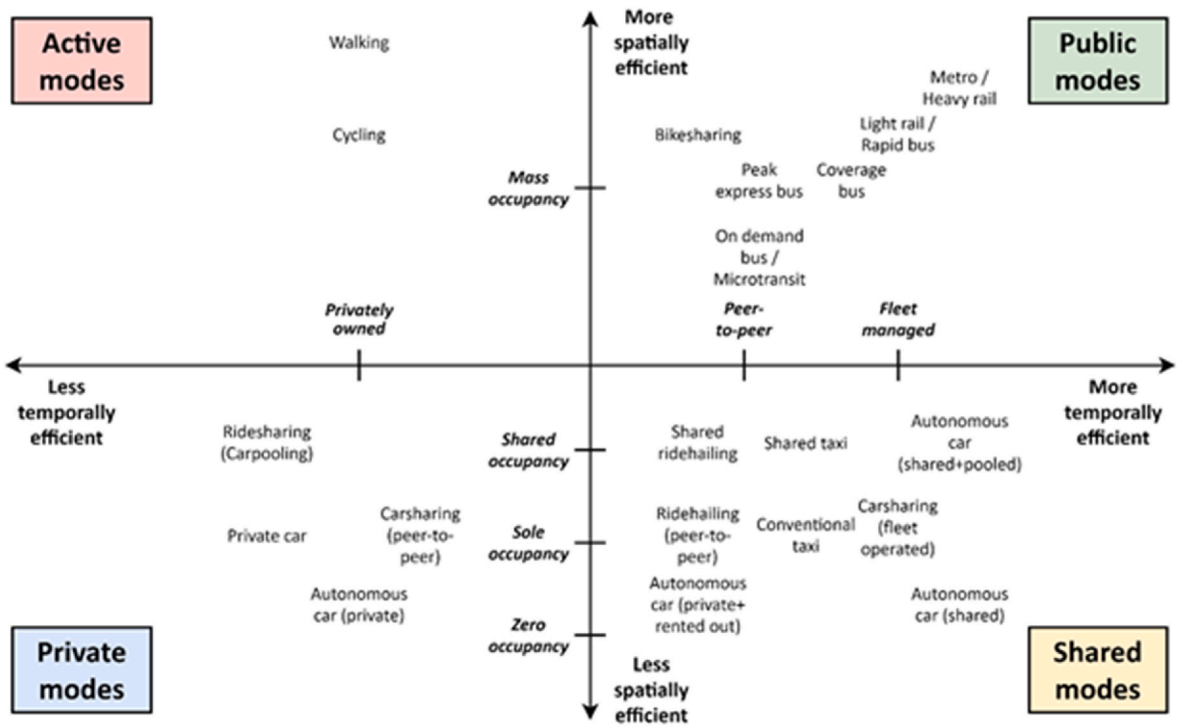

Fig. 1. The efficiency of different transport modes for moving people (source: Wong et al., 2020).

components previously performed using active modes. This so-called "modal displacement" has a negative impact on the decarbonization of passenger mobility, but also on health and social inclusion (Hensher et al., 2020; Tirachini, 2020).

Regarding the role of active mobility in the development of MaaS packages, by reducing the use of cars, walking and cycling provide environmental benefits associated with reductions in air pollution, traffic noise and congestion. Moreover, active mobility has multiple health benefits from increasing physical activity, with spillover effects on reducing health costs and work absenteeism (Mueller et al., 2015). Therefore, the encouragement of active mobility should be centerpiece in MaaS systems that have sustainability purposes. In the case of cycling, the potential of bikes to facilitate multimodality – which is in the core of MaaS developments-has been unambiguously shown in the literature, as cycling enlarges the catchment area of public transport far beyond a catchment area defined by a 'walkable' distance (Geurs et al., 2016; Kager et al., 2016). Even though in several countries most cycling trips are door-to-door (i.e., trips that involve cycling only), the potential of multimodality involving the use of bicycles and public transport is large in both planning and design of infrastructure (Kuhnimhof et al., 2010). This is because cycling infrastructure could enhance the quality and quantity of bicycle routes, and bicycle parking facilities at train stations can significantly increase train demand and accessibility to jobs (Geurs et al., 2016). To illustrate this potential, Kager et al. (2016) show that while 19% of the population in the Netherlands lives within a 1 km network distance from a train station (walkable distance), 69% of the population live within 5 km of a train station (cyclable distance). Furthermore, the advent of electric bikes can enlarge the catchment area of public transport even more. It is therefore clear that the integrated planning of public transport, shared bikes and shared e-bikes emerges as a topic of increasing relevance in the future, with MaaS potentially having a relevant role, for instance by setting convenient pricing packages that encourage the use of shared bicycles and public transport for medium-to short-distance trips in an integrated way.

It is unlikely that all the modes depicted in Fig. 1 would be present in a city transport network at the same time. Thus, how MaaS may look in different geographic settings and cultures will depend on their mobility landscape and how MaaS is designed and implemented. The mobility landscape is quite different between developed and developing countries, which is likely to shape differences in MaaS implementation pathways, as discussed in Section 2.2. Can multimodality help to reach decarbonization goals? In this regard, the case for a combined use of public transport and active modes is clear, either for different trip types (active modes for short trips, public transport for long trips) or in an intermodal way (active modes to reach public transport stations). However, the combination of public transport and active modes to address mobility need and decarbonization reflects the concept of Transit Oriented Development (TOD) more than that of MaaS. We discuss how the MaaS framework may help decarbonize the transport sector in developing countries (section 4) after analyzing the existing evidence on MaaS potential (remaining of section 2) and the transport market in developing countries (section 3).

2.2. MaaS: current findings and outlook

The extent to which MaaS facilitates multimodality and helps the transport sector reach decarbonization goals will depend on how MaaS is designed and implemented. To this end, it is important to recognize the different levels of MaaS integration because the potential benefits that MaaS promises to its end-users strongly link to the level of integration that a MaaS product aims to offer. The literature identified the following four levels of MaaS integration (Sochor et al., 2018; Ho et al., 2021b; Lyons et al., 2019).

(1) Integration of information.
(2) Integration of booking and payment.
(3) Integration of services.
(4) Integration of societal goals.

A highly integrated MaaS product (levels 3 and 4) provides more benefits to the users, mainly through improving customer experience and allowing for a greater optimization of the transport network. Such a product, however, requires more resources to develop, and hence may not be suitable for all settings, particularly in places where the budget for transport and new initiatives is limited.

A lower level of integration offers MaaS users an ability to search (level 1), book and pay (level 2) for single or multiple services using a smart MaaS app. Herein lies the need to recognize the difference between vertical and horizontal integration of mobility services. *Whim* is an example of horizontally integrated MaaS in that *Whim* serves as a digital market platform for creating new markets and services within the distribution network involving multiple transport service providers. By contrast, Uber could be vertically integrated by acquiring assets or services of other suppliers in the value chain (e.g., Uber acquired bike sharing startup Jump and a peer-to-peer car-sharing platform Car Next Door, which are all modes that could be part of a MaaS package). By bringing together multiple transport services into a single platform that may combine vertical and horizontal integration, MaaS aims to leverage digital technology to create value-adding for every stakeholder involved, ranging from travelers to transport service providers and the society (Ho, 2022).

Evidence to date suggests that travelers value the convenience of a MaaS app,[3] but they are not prepared to pay for it (Ho et al., 2018, 2020). This research evidence is in line with commercial practices in the sense that the world-first MaaS operators, MaaS Global and UbiGo 2.0 who commercialize MaaS in Helsinki and Stockholm, respectively, do not charge their users for using their MaaS app. Neither do Uber, Grab, Ola, DiDi and the similar services that charge the user directly, although at the point of use, the user pays for these services and the app providers take a fee, typically as a percentage of the journey fare as in a revenue-sharing agreement with drivers. These research findings and real-world evidence support the notion that MaaS is more than just an app (Hensher et al., 2020). This means that it may not be financially viable to develop and monetize MaaS app without offering mobility services, particularly in markets where travelers can access and use, for free, well-functioning multi-modal journey planner apps (e.g., Google Maps, Moovit, Citymapper) and/or web-based services. At the same time, the MaaS literature generally agreed that a MaaS app is a necessary condition for the development and implementation of any mobility services that could be considered a functioning MaaS, as opposed to a MaaS in-development (Hensher et al., 2020).

This poses the question of who would likely be early adopters of MaaS? And, related to this question, can MaaS facilitate multimodal behavior to achieve decarbonization goals? A few stated preference (SP) studies and real-world trials point to shared characteristics of early MaaS adopters in different countries (Ho et al., 2018, 2020; Guidon et al., 2019; Caiati et al., 2018; Matyas and Kamargianni, 2019). MaaS users typically exhibit multimodal behavior, are concerned with the environment and a healthy commuting lifestyle, and do not see car ownership important. For example, the vast majority of the people that signed up for the Sydney MaaS 6-month trial were frequent users of both public transport and private cars. In addition to habits and attitudes, other studies also found the association between socio-demographics and the propensity to adopt MaaS, with younger and more highly educated adults (both links to digital literacy and competency) being more likely to be early adopters (Strömberg et al., 2018; Alonso-González et al., 2020; Zijlstra et al., 2020). At the same time, in developing countries there is minimal evidence on the potential adoption of MaaS. Based on a stated preference survey on university students in Brazil, Gandia et al. (2021) find that a MaaS implementation would be attractive for both car users and non-car users, as this young and educated segment of the population values MaaS features such as app payment, customization, monthly plans and mode integration. Car owners were more inclined to adopt MaaS if they did not use their cars daily. Regarding actual MaaS implementations, Brazil had the app Quicko, used by 500,000 people in the country, with level 2 MaaS integration, according to a self-report.[4] Eventually Quicko was shut down in late 2022, six months after being acquired by MaaS Global.[5] To date we find no independent study on the travel behavior and transport sustainability effects of actual MaaS implementations in developing countries.

These findings support the notion that multimodal travelers are more interested in MaaS than others,[6] and contradict the fear that MaaS does not appeal to car owners and/or frequent car users. Indeed, 82% of the Sydney MaaS trial participants had daily access to private cars. Of these, 35% subscribed to monthly mobility bundles that were designed to provide a financial incentive for the subscribers to alter their travel choices towards more sustainable modes. As a result of subscribing to a monthly mobility bundle, the trial participants were found to reduce their monthly private car kms (Hensher et al., 2021a) but increase their monthly ridesourcing use (Ho, 2022), owing to the discounts for the use of ridesourcing included in the MaaS packages. However, in total, the increase in ridesourcing use was smaller than the reduction of private car use. Also, 17% of the participants who owned a car reported that the experience of the trial changed their view of car ownership, with most of these participants stating that they would have purchased one of the trialed bundles if they became available on the market post-trial. These findings support MaaS as a pathway to reduce private car ownership and car use, and hence achieving societal goals of decarbonization and reducing congestion. Achieving these goals would require proper travel behavior incentives in order to avoid or reduce the effect of an increased use of shared car-based modes. A high level of MaaS integration (Level 3 or 4) is needed, which in turn requires a proper data sharing scheme and governance.

2.3. Data sharing and MaaS governance

Data sharing enables digitalization that powers MaaS. At the lowest level of integration, a MaaS product combining multi-modal services must offer informational integration. Thus, the first step in the roadmap for MaaS is to have legislation aiming at data sharing and open data to enable the digital economy and link MaaS to the wider context. Indeed, Finland, the birthplace of the first commercial MaaS, passed the *Act on Transportation Services* in 2018 which sets open data requirements for all transport providers so that users can acquire different services from a single point of sale (Rautavirta and Kaivola, 2018). This legislation helps speed up the commercialization of MaaS, first in Helsinki and now expanding to other cities around the world. An introduction of similar legislation in developing countries is likely to help the development of MaaS by enforcing not only data sharing but also a data standard. The latter will allow developers, be them MaaS aggregators or third-party companies such as Moovit and SkedGo, to manage the integration of data and transport services from stakeholders and offer a multimodal journey planner – a precursor for any MaaS product.

Next, regulations around ticketing and reselling of tickets will need to be revised so that the MaaS aggregator/broker can package different transport services into mobility bundles and resell these to the end-users. Depending on who will take on the MaaS aggregator role, a revenue sharing/funding model may be needed to allow private transport service operators to assess the benefits and costs of becoming part of the MaaS

[3] It is important to distinguish a digital platform, typically in the form of a smartphone app, from a MaaS product. The latter includes the former as part of the offer; however, MaaS is not simply an app that offers journey planer and/or payment features (such as Uber, DiDi, Lyft).

[4] https://whimapp.com/news/maas-global-enters-brazil-by-acquiring-quicko/, accessed June 7th, 2023

[5] https://www.transportxtra.com/publications/local-transport-today/news/72160/maas-global-creator-of-maas-app-whim-lays-off-staff-as-it-re-organises-/, accessed June 7th, 2023

[6] Independent research on ridesourcing adoption also finds that multimodal travelers are more likely to use ridesourcing platforms, see, e.g., Conway et al. (2018) and Sikder (2019) for the United States, Young and Farber (2019) for Canada, and Tirachini and del Río (2019) for Chile.

offering, either as a MaaS aggregator and/or a service provider within the MaaS offering. In this context, very little information is available in the literature to elaborate on, mainly due to commercial confidentiality. Findings from stated preference surveys and in-field trials of MaaS suggest that a commercially viable business model for MaaS should carefully develop a cross-subsidy strategy to create attractive mobility bundles by using benefits gained from one or multiple services to support other loss-making services (Ho, 2022).

The Public Private Partnership (PPP) is another funding model that could be used for MaaS in that the public sector funds societal objectives, run public transport services both inside and outside the MaaS offering while the private sector commercializes MaaS (Aapaoja and Eckhardt, 2017; Ho et al., 2020; Ho, 2022). The private partner could be an existing transport operator or third-party MaaS company that does not operate any transport services in the local market. It is noted that few independent surveys of potential aggregators conducted to date (Wong and Hensher, 2021; Narupiti, 2019; Jittrapirom et al., 2017) support the private sector to take a lead role as a MaaS aggregator/broker, ideally with support from the government, either through development funds or the inclusion of traditional mass public transport in the MaaS offers. A usual concern with the government taking a MaaS aggregator role relates to the lack of incentive to innovate, slow process and unpredictable outcomes (Hensher et al., 2020; Narupiti, 2019), although there is no evidence of this being actually the case, because, to our knowledge, no government anywhere has taken on the MaaS aggregator role. The two emerging cases are the large-scale MaaS trials under development in Minnesota, USA and Sydney, Australia which appear to see the leading role of the local transport authorities in aggregating the mobility services, in close collaboration with private providers (Phillips, 2021, McFadden). Who will take the MaaS aggregator role remains a big question, even more so in developing countries where the transport markets, discussed below, differ significantly from those in developed world where most MaaS studies have been conducted.

Central to a fair and transparent funding and revenue sharing model for MaaS is the capability to provide data services. Herein lies the need to manage data and provide data analytics services that could inform strategies for market segmentation (maximize revenue) and minimizing operational costs of running the service at scale in terms of customer service, supplier relationship and integrations, and improving the MaaS app. While capable of managing and using their own data, most existing transport service providers in developing countries are too small to extend themselves to become a data provider that is also capable of data integration and analytics. In developing countries where data sharing and open data are new, it is expected that variations in technical readiness exist across transport service providers and this represents a big issue, and hence cost, for integration. Thus, more investment in data infrastructure, such as data exchange center and open data hub, is required so that MaaS can leverage digital technology and network optimization to create value for users and improve customer service.

3. The transport sector in developing countries

3.1. Characteristics of the transport system in developing countries

It is widely recognized that the transport sectors in developed and developing countries fundamentally differ in terms of the level of (in)formality, regulation, quality of infrastructure, level of involvement of the public and private sector, safety, and so on. Even more, within the developing world, transport networks and systems vary greatly across countries and even cities within the same country. In the case of public transport, its social role as providing affordable access to education, employment, health services and leisure activities, is more relevant in societies with a lower level of access to private cars, as it is the case of developing countries that usually have a high public transport modal share, therefore making public transport work properly should be of high priority within their transport sectors (Gakenheimer, 1999). Two situations are observable in terms of organization of the transport sector and levels of development.

a. Environments with an unregulated (or poorly regulated) informal public transport market, which typically have a high share of public transport trips, e.g., microbuses in some African and Latin American countries and cycle rickshaws in Southeast Asia. These informal markets are particularly common in locations with low motorization rates, and consequently a low modal substitution between cars and public transport but higher modal substitution between public transport, walking, cycling and other two-wheelers.
b. Developing countries with regulated formal public transport systems in their main cities, often featuring higher standard of service in the form of high-frequency Metro (subway) systems and/or Bus Rapid Transit (BRT) systems. These systems represent a better quality of rolling stock with lower levels of congestion and pollution externalities than those found in unregulated markets such as minibus, tuktuk and riskshaw.

Given the mix of modes used to provide public transport services, the sustainability analysis of public transport should take into account the technology and type of the rolling stock used to account for the different levels of externalities attached to transport services in regulated and unregulated markets (Parry and Timilsina, 2010). It is also worth noting that formal and informal public transport services coexist in several developing countries, with sharp differences in quality of service, fare level, safety, size and type of vehicles (Tirachini, 2019). Thus, the journey to a multimodal future will look completely different for one city to the next, depending on its mobility landscape, existing mobility patterns, and how MaaS is designed and implemented. It is therefore crucial that the MaaS framework recognizes the importance of the existing mobility setting found in each city to reach decarbonization goals through multimodality and carbon strategies that are specific to each city.

For the development of carbon strategies specific to each city, Fig. 2 shows how the mobility landscape and mobility patterns vary across cities, using only a few cities in developing and developed countries for illustration and one single metric: the modal split. Within the developing world, the share of urban trips by public transport varies significantly, with a modal share of public transport usually high in South American cities (between 28% and 72%) and usually low in Southeast Asian cities (4.7%–17%) where public transport services are poorer and motorcycles are much more prevalent, accounting for between 40% and 81% of urban trips. Urban trips by private car account for between 4.4% and 25.8%, which is a wide range. The transport networks in developing countries in Southeast Asia such as Bangkok and Hanoi could be characterized as private-vehicle centric, while those in South America are much less dependent on the private vehicle, with some cities such as Santiago and Curitiba having well-connected public transport networks that serve a significant percentage of travel, with different levels of quality-of-service. Trends in the evolution of modal shares are sometimes different between regions. For instance, while some European capitals such as London and Paris have managed to reduce car trips and increase public transport trips, the opposite is happening in South American and Southeast Asian capitals such as Santiago, Buenos Aires, and Hanoi (Tirachini, 2019; Ngoc et al., 2021). Moreover, in Brazil and Colombia, the rate of growth of motorcycles is more than double the rate of growth of cars (Hidalgo and Huizenga, 2013), which is a challenge for traffic safety and decarbonization if motorcycles are used for door-to-door travel (as observed in many cities in Southeast Asia such as Hanoi, HCMC and Jakarta). An appropriate carbon strategy for these cities should aim to improve public transport services and encourage residents to use motorcycles as a way to access public transport services instead of as a door-to-door mode.

In summary, identifying the roles of public transport services vs. private modes in a city mobility landscape is critical for developing a

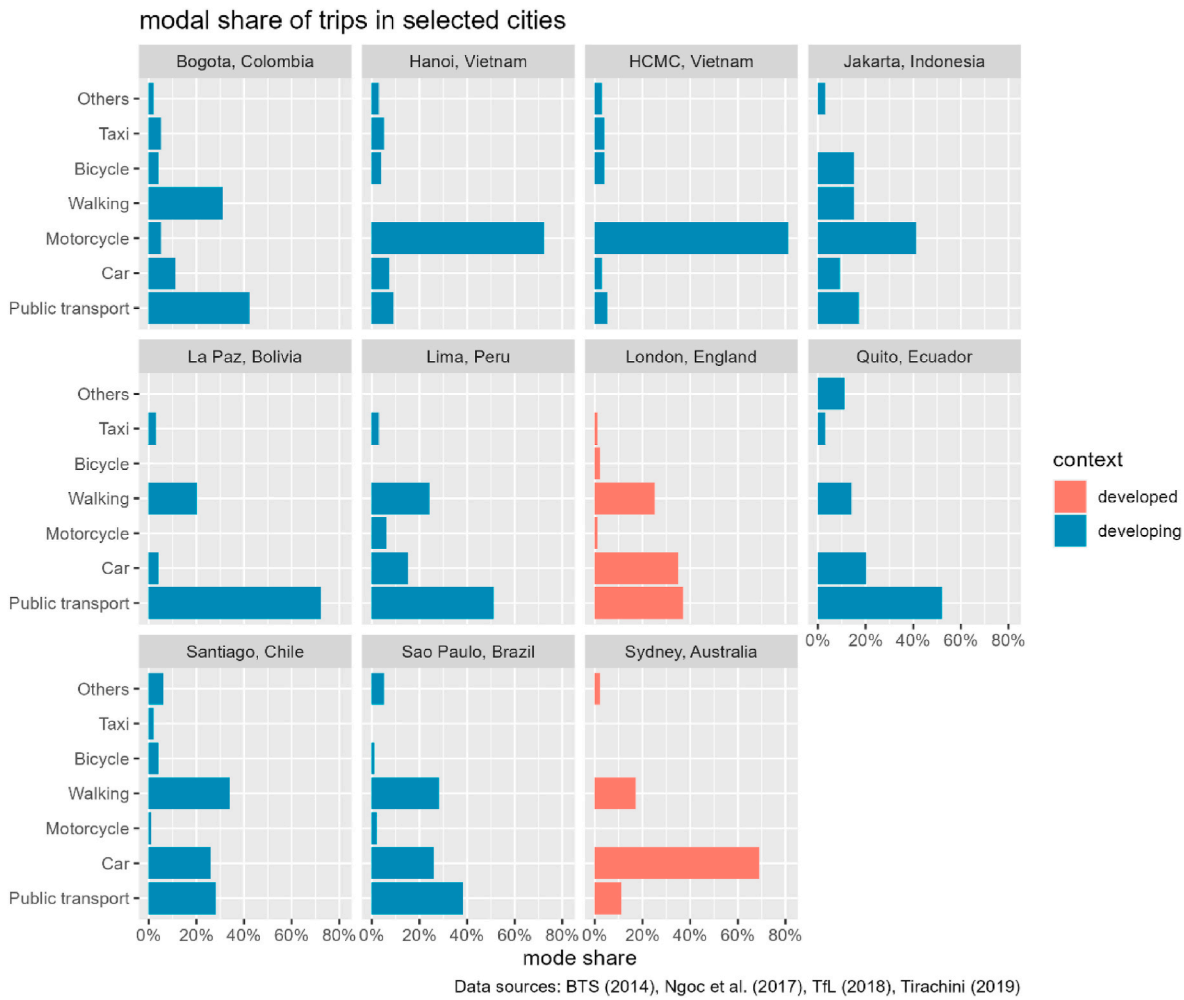

Fig. 2. Modal split of trips in selected cities.

MaaS product and carbon strategies that contribute to the decarbonization goals. Generally, in car first cities (e.g., North America, Australia) or motorcycle first cities (e.g., Hanoi, Jakarta), MaaS should aim to move point-to-point transport from private to shared modes. By contrast, in a public transport first cities (e.g., Europe, South America), MaaS should not replace (formal) public transport. Instead, MaaS should leverage the temporally more efficient mode such as ridesourcing and carsharing to replace private modes. These are the type of travel behavior changes that should be encouraged by modal integration efforts if the objective is reaching a more sustainable and decarbonized mobility situation.

3.2. Barriers for the implementation of MaaS in developing countries

The reduction of negative traffic externalities and car ownership, and the increase of social equity are usually suggested as desired outcomes for MaaS implementations (Butler et al., 2021). Barriers and risks have been identified for reaching such outcomes in the scientific literature that analyze MaaS schemes in developed countries. The characteristics of developing countries make the analysis of MaaS and prediction of its outcomes even more complicated. For instance, taking the case of Bangkok in Thailand, Narupiti (2019) concluded that "a lot of things have to be done" before MaaS can run parallel with or supplement to the existing transport services. These range from IT platform to data standard to regulation and revenue sharing model (see Section 2.3). These challenges should be taken in the context that Bangkok is a megacity of 13 million people, many of whom suffer from long travel time and distance, partly due to the disconnected transport services that are operated by different providers who use their own digital apps.

The unstructured, underfunded, and fragmented transport market found in many developing cities is both an opportunity and a barrier for MaaS. The opportunity lies in the fact that MaaS can be used to create value for customers and service providers by uniting fragmented services into a single and intuitive platform that people can use to make their everyday travel easier, quicker, and more affordable.[7] Thus, for developing cities with a decent public transport quality, the journey of MaaS should start by introducing some basic features of MaaS such as multi-modal journey planner and booking (i.e., to reach MaaS integration levels 1 and 2, see Section 2.2) before aiming to provide a higher level of integration.

The barriers take several forms. To improve public transport accessibility and usability with MaaS, it is necessary to have an integrated transport network that offers travelers an appealing transport solution in terms of cost, travel time, reliability, convenience, and comfort. Obtaining an integrated transport network should be an objective of MaaS, that appears to be well understood by most stakeholders, including those in developing countries (Narupiti, 2019). However, the fact that formal and informal forms of public transport might coexist and

[7] Non-transport services (e.g., retail, food, entertainment) sometimes are also integrated with multimodal transport services in one single app. Gandia (2021) suggests that in developing countries, such a multipurpose platform would be more attractive for car owners than a transport-only platform.

compete with each other in developing countries implies that the formulation of transport policy, the planning of transport networks and the setting of optimal financial incentives (road prices, fuel taxes, public transport subsidies) is more complex than in cities in high-income countries where most, if not all, public transport modes are formal and regulated. Certainly, the problems derived from informality and lack of financial resources extend to a potential implementation of MaaS in such contexts. For example, Parry and Timilsina (2010) adapt the optimal public transport subsidization model of Parry and Small (2009) to the analysis of formal and informal public transport markets in Mexico City, and find that the large fleet of poorly regulated profit-maximizing microbuses are an important source of congestion and pollution, and therefore should be taxed instead of subsidized (in spite of their effect on easing automobile congestion). Security problems attached to poorly performing public transport systems in developing countries are also an issue, because if passengers feel much safer traveling alone (e.g., in ridesourcing), a large portion of travelers will not prefer shared mobility or public transport options if given the chance. In this context, regulations aimed at improving the security of passengers in shared modes are required (Acheampong, 2021).

It is thus clear that a successful implementation of a MaaS scheme in countries with high-quality public transport (e.g., Western Europe) is unlikely to deliver the same results in countries with low-quality public transport or in which formal and informal forms of public transport coexist (Gandia, 2021). Ridesourcing and car sharing have a larger chance to replace rather than complement public transport in cities where the public transport service is poor (Tirachini, 2020; Acheampong and Siiba, 2020), whereas travelers in cities with a robust and reliable public transport service have a larger chance of using car-based modes as feeders for mass public transport. Intermodal trips that include public transport and shared mobility, which can be promoted with MaaS depending on the design of the MaaS scheme, can be a step in the right direction if the objective is reducing negative traffic externalities though MaaS, as the example in Section 5 illustrates. On the other hand, applying MaaS straightaway in cities with poor-quality public transport (or in which formal and informal public transport provision coexist) is a likely recipe for an increase in negative traffic externalities, due to a large modal displacement towards car-based modes.

The previous discussion illustrates that, in developing countries, a necessary condition for multimodality agreements and the formulation of MaaS packages is the general improvement of the public transport service and the formalization of the informal public transport sector, in order to significantly improve its quality and reduce its negative externalities. Otherwise, if an informal public transport persists, a potential implementation of MaaS will be spatially constrained to those locations where public transport operates formally and frequently (only to BRT and Metro lines), limiting its spatial coverage and posing social equity issues. In the case of ridesourcing, a condition for any MaaS agreement should be the regulation of ridesourcing services and the formalization of the job of drivers, given that informal working conditions lead to safety and security risks, as shown in countries such as Chile (Fielbaum and Tirachini, 2021; Fielbaum et al., 2023)[8] and Ghana (Acheampong, 2021).

In the case of South Asia, the coexistence of informal and formal services could partially be explained by the requirement of keeping a low fare (for social reasons) without a structured subsidy, a system that strains the capability of operators to maintain service and coverage (Gwilliam, 1999). Budget constraints, therefore, attract an uncontrolled informal sector to supplement formal supply. This issue, together with inefficient operation and management, has led to the collapse of several public companies. It is therefore clear that the lack of public subsidies to support formal public transport will be a key limitation for the implementation of MaaS and multimodal frameworks in the future of the developing world.

In this context, understanding the roles of different transport modes in each geographic setting, and the institutional and social frameworks behind them, is critical for the design and implementation of MaaS and multimodal future, especially when MaaS is targeted at specific population characteristics such as low income or car-free households. For example, for cities with a decent public transport network but being dominated by private vehicles, MaaS can help by integrating different transport services in a seamless way, effectively providing its users a multimodal solution as an alternative to the private vehicle. By contrast, for cities where public transport accounts for a larger market share, MaaS can help promote public transport by leveraging the temporally efficient modes such as (shared) ride-hailing or on-demand buses to address the first-mile and last-mile connections and feed passengers to trunk public transport services. This strategy is particularly effective for promoting multimodality while improving customer experience, particularly for those who are willing to use public transport but are deterred by the effort, time, and/or cost of accessing these services. In the case of developing countries, it is expected that this potential demand is mostly constituted by middle- and high-income households, as low-income households tend to be public transport dependent already. In all urban settings of developing countries, public transport modes should constitute the backbone of multimodal services due to their spatial and temporal efficiency but also their affordability, stemming from its scale economies.

3.3. MaaS and the issue of social equity

If there are questions about the relationship between new mobility platforms and social equity in developed countries (Pangbourne et al., 2020; Ho et al., 2021b), this issue is expected to be even more complicated in developing countries, as current practices from ridesourcing, bike-sharing and scooter-sharing providers portrait a grim picture. For instance, in Latin America and other regions of the Global South, bike-sharing and scooter-sharing tend to be deployed or focused only on middle- or high-income areas in large, segregated cities (as shown for Santiago by Mora and Moran, 2020). The same happens with commercial online delivery platforms that tend to ignore low-income areas, which has prompted municipalities to organize and subsidize teams of local bicycle riders to provide delivery services to local businesses (e.g., the case of “Pídelo en Cleta”[9] in Renca, a municipality in the west part of Santiago). In highly segregated cities as those in Latin America, the prospects of commercial shared-mobility or MaaS platforms avoiding low-income areas altogether is indeed a huge challenge from a social equity point of view. While difficult, it is possible to design a MaaS ecosystem that has sustainability goals and does not limit interest and participation from any socio-economic (linked to social exclusion) or geographical (linked to spatial justice) segment of society (see Ho et al., 2021b for an example). Therefore, referring to the sustainability triple bottom line in the pursuit of economic, social and environmental goals, it is clear that the public sector needs to be involved to secure at least social and environmental goals in the potential deployment of MaaS in developing countries (Pangbourne et al., 2020). This is because when/if left to private entrepreneurs only (whose main interest is profitability), it is possible that the outcome is an increase in motorized traffic (against environmental goals, see Section 4) and a lack of *ethical design* (Sgarro, 2018), which exacerbates social exclusion and is against social equity (e.g., services avoid low-income households in the case of shared mobility

[8] Based on a survey of ridesourcing drivers in Chile, Fielbaum and Tirachini (2021) find that most drivers have been subject to risky situations while working and that, given that the working time is only self-regulated, a significant rate of drivers work 11 or more hours driving a car in a day, which is a health and safety hazard. Moreover, combining all the jobs that drivers have, one out of four respondents reported working more than 60 h per week.

[9] https://renca.cl/pideloencleta/, accessed June 7th, 2023.

platforms).

As it is unlikely that such an equity-seeking MaaS system will work without the setting of proper public subsidies in the developing world, it follows that the public sector involvement implies not only regulation but also financial backing. These resources may come from new user charges or taxes applied to low-occupancy car-based modes (e.g., ride-sourcing taxes, road charging for cars). If a multimodal MaaS-like mobility system does not consider such new revenue streams, in countries with scarce or no public funds available for the transport sector, the most likely result will be an exacerbation of social inequity because MaaS will be left to profitable niche markets only. Therefore, in a way, MaaS could be used as a catalyst for a broad environmental and equity-seeking transport pricing reform, that points to pricing car use (that in developing countries tend to be concentrated in middle- and high-income households) at the same time of subsidizing sustainable modes and bringing shared-mobility options to low-income households.[10]

Note that the latter includes bringing car-based platforms such as ridesourcing to lower-income populations that today lack access to cars, which might be considered as more equitable than the status-quo. Therefore, if not properly managed, new MaaS packages in developing countries may end up with a situation in which its social objective (i.e., equity) conflicts with environmental sustainability (i.e., decarbonization). To prevent the undesired outcome of higher access to car-based modes through MaaS worsening traffic conditions and the environment, we argue that some form of road-pricing scheme is needed to internalize the external costs of car traffic (i.e., congestion, pollution, and other negative externalities). Ideally, a distance-based pricing scheme that reflects the different marginal costs across time and space is preferred but other schemes including cordon-based charge and/or vehicle ownership levy could be used to correct the market failure. Internalizing the external costs of transport into user prices is a key element to make our transport systems more sustainable in social, environmental and economic terms (Becker et al., 2012). This conflicts with current MaaS products that attach value to the simplicity of a pricing scheme that provides flat-fare products that have trips with zero marginal cost for its users. Therefore, from an equity, environmental and economic efficiency point-of-view, limited use of those pricing schemes should be made. If/when used, such flat-fare scheme should only target so-called sustainable modes (public transport, active modes) as there is no case on sustainability grounds for flat fares in the case of shared cars, ride-sourcing, taxis or any other car-based modes, even though there might be a market for such schemes from a private-profit perspective. The next section discusses the use of several pricing mechanisms that MaaS can leverage to obtain societal goals including decarbonization.

4. MaaS prospects for decarbonizing transport in developed and developing countries: potential benefits and risks

There are a few mechanisms within a MaaS framework that can be used for decarbonizing the passenger transport sector. Based on Ho et al. (2021a,b), selected pricing mechanisms that can play in favor or against decarbonization purposes are identified in Table 1. The final effect on the level of traffic-related environmental externalities depends on the design of each mechanism, i.e., if the scheme incentivizes the use of so-called sustainable modes (public transport, bicycles) or the use of single-occupancy car-based modes (e.g., taxis, ridesourcing). It is worth emphasizing that not all the mechanisms are available within a given MaaS ecosystem because each mechanism must be built before the corresponding lever or levers can be pulled to design a MaaS product, whether it is a mobility subscription bundle, a Pay-as-you-go (PAYG) alternative or any other features the MaaS platform would offer to its users. For example, a scheme currently used by commercial MaaS providers is the combination of *capped fare*, *subscription* fee, plus *discount* per *mode* mechanisms. One such case is charging a fixed subscription fee in return for unlimited use of public transport for a period of time (e.g., a month), and discounted fares/special offers for other services such as car rental, car sharing and bike-sharing.

Table 1
Selected pricing mechanisms in MaaS bundles and potential effect for decarbonization.

Lever	Description	Mechanism	Decarbonization effect
Ticket cost	Participants pay for singular trips, when necessary	Fixed discount (inc. 0%) applied per trip	Positive if discount per trip is applied to sustainable modes only
Fixed unlimited cost (or flat-fare)	Fixed cost to gain unlimited access to a mode	Fixed discount (100%) and subscription fee	Positive if unlimited access is provided to sustainable modes only
Fixed access cost	Fixed cost to gain access to other discounted prices (like subscription cost)	Fixed discount + subscription fee	Positive if discounts favor the use of sustainable modes
Capped trips	Pay $x for trips costing up to $y (x < y)	Capped fare per mode	Potentially negative if capped fare is applied to single-occupancy car-based modes
Capped discounts allowance	Users have a capped amount per month to use at a discounted rate (with PAYG rates after)	Capped allowance per mode	Potentially negative if discount is applied to single-occupancy car-based modes
Fixed discount	Take a fixed amount off (in absolute or percentage terms) the cost per mode/trip	Fixed discount amount per mode	Potentially negative if discount encourage the use of single-occupancy car-based modes
Time-based incentives	Apply discounts based on the time the trip is taken	Fixed discount percentage by time period	Positive if applied to sustainable modes, e.g., off-peak public transport trips
Unlimited access	Upfront cost of $x allows unlimited access (partial access) to all modes	Fixed discount (inc. 100%) + subscription fee	Unknown up front, behavioral changes with unlimited access may increase or reduce motor vehicle use

Note that some mechanisms, such as fixed discount and subscription fee with unlimited access to greener modes are effective for promoting sustainable choices in some cities but not others, depending on the existing mobility landscape and travel patterns found in each city (see Section 3.1). For example, in cities where public transport is well developed but underused (such as Jakarta, Sao Paulo, and Sydney), a flat-fare or an off-peak discount for public transport would encourage people to replace car trips with public transport trips, and hence reducing emissions; however, the same mechanisms would not be effective for cities where the public transport network, particularly formal public transport using low-emission vehicles, is not well developed (e.g., Hanoi, Lima, Johannesburg). Research evidence from the few real-world trials of MaaS supports this in that flat-fare tends to be preferred by users due to its simplicity and the potential saving of monthly transport costs but this preference is observed only in cities with a good public transport network (Reck and Axhausen, 2020; Caiati et al., 2020). In cities with a poor formal public transport network such as Johannesburg, fares do not appear as one of the main reasons for not using public transport (Walters and Pisa, 2022). Therefore, offering a flat-rate or discounted fare would worsen the problem of insufficient public subsidies for facilitating formal public transport, which is the primary barrier to implementing MaaS as discussed in Section 3.2.

Similarly, some mechanisms are easier to implement in practice in that they require fewer resources to implement than others, and this has

[10] See, e.g., Tirachini and Proost (2021), who show that in the presence of income inequality aversion, both the public transport subsidy and the fuel tax should be increased in Santiago.

an implication on costs and benefits of MaaS, which is discussed in Section 3.3. An interesting contradiction emerges here, because, on the one hand, simplicity is a strong explainer of users' preferences for flat fares, which can be used to incentivize modes such as public transport and shared bicycles, but on the other hand, flat fares take us away from user-based marginal cost pricing, precisely when, by the first time in history, a low-cost technology that enables the identification of external costs on a trip-by-trip basis is widely available (Hörcher and Graham, 2020; Hörcher and Tirachini, 2021).

The simplicity and appeal of flat-fare multimodal bundles also pose a risk for decarbonization purposes, as the inclusion of single-occupancy car-based modes (such as car sharing) in this zero-marginal-cost fare structure design might very well increase the number of vehicle kilometers traveled (VKT) by the MaaS user, and therefore exacerbate negative externalities related to motorized traffic (Hörcher and Graham, 2020). Proper mode-specific pricing incentives, which avoid overconsumption of single-occupancy car-based modes, are critical in this context to strike the right balance between the appeal of the MaaS concept and the pursuit of decarbonization objectives. Private profit and social welfare goals may collide in the optimal design of environmentally friendly MaaS products, which calls for involvement and/or leadership of the public sector in the planning, provision, and pricing of MaaS services.

Even though MaaS has been promoted as a digital platform that could help decarbonize passenger mobility through changing users' travel behavior towards more sustainable choices such as less private car use and more walking, cycling and public transport, the present analysis shows that reaching that goal depends on the design of the final MaaS products that are offered. In practice, there are a handful of studies that assessed the impact of MaaS on travel behavior, with even fewer studies assessing MaaS potential for decarbonization of passenger mobility (see Ho, 2022 for a comprehensive review). In order to make a full environmental analysis of MaaS, it is worth highlighting that the *net* impact of MaaS on the environment is what matters because any reduction in private car use may be offset by higher use of other carbon-heavy modes such as car-sharing, car-rental, ridesourcing and taxi. This offset effect is possible as Strömberg et al. (2018) and Smith et al. (2021) find qualitative evidence from the UbiGo and EB2C MaaS trials, respectively, that indicates participants replace not only private car trips but also public transport trips with car-sharing and bike-sharing services. Early quantitative study has found evidence of this offset effect and the net impact of MaaS bundles on the use of carbon-heavy modes is still negative (Ho, 2022). If reproducible in other settings with comparable MaaS products, this promising finding shows MaaS prospects for decarbonizing the passenger mobility sector.

The simulation study by Becker et al. (2020), using the activity-based simulation model MATSim (Horni et al., 2016) and hypothetical scenarios in the city of Zurich, found that through a less biased mode choice alone, MaaS has the potential to reduce transport-related energy consumption by 25%, and the addition of car-sharing and bike-sharing schemes may increase transport system energy efficiency by up to 7%. Regarding empirical evidence from real MaaS products, perhaps the most concrete evidence to date of MaaS impacts on travel behavior and the environment are the two studies that leverage usage data from the Sydney MaaS trial. Hensher et al. (2021a) reported that bundle subscribers reduced their private car kms, with an average reduction of 29 kms per subscriber per month for a 10% increase in the probability of choosing a monthly bundle. Ho (2022) further showed that MaaS subscribers reduced their car-based monthly kms and trips while increasing the use of shared modes, particularly taxi and ridesourcing. These changes in travel behavior result in an environmental benefit, with an average reduction in CO_2 emission per subscriber per month being 57 Kg. This environmental benefit, however, was not observed for pay-as-you-go users, who were offered the same smartphone MaaS app but chose to pay per trip with no discount and no subscription fee, and hence no commitment to travel more sustainably.

While existing studies reviewed above offered some quantitative and qualitative evidence on the benefits that MaaS can bring to the users (such as saving transport costs – see Becker et al., 2020), to the transport service providers through extra revenue (Ho, 2022), and to the environment (Hensher et al., 2021a; Reck et al., 2021; Ho, 2022), these studies provided only a fragmented picture of MaaS benefits. Specifically, all studies ignored the long-term impacts of MaaS on land use (such as how MaaS may change residential and workplace choices) and the medium-term impact on private vehicle ownership (with the exception of Hörcher and Graham, 2020, who study MaaS effects on car ownership through a simulation study, not attached to any real MaaS situation). These long-term impacts would constitute most of the benefits that MaaS can bring about by reducing traffic congestion, shortening travel time, reducing road crashes and increasing travel time reliability. One possible way to account for these benefits would involve the use of a strategic travel demand model that includes MaaS as a mobility option, together with existing services, for all or part of the population that MaaS targets, so that the full impact of MaaS can be modeled to obtain input for cost and benefit analysis. Thus, we conclude that the potential contribution of MaaS to society via reducing car ownership and improving environmental sustainability in the long term remains unknown.

Collectively, the early evidence points to two relevant conclusions. First, that if/when scalable, MaaS could be used as a tool to reduce environmental externalities from the transport sector, at least in the short term. However, looking forward, it is unclear at this stage if MaaS alone can have any significant effect on sustainable travel behavior, beyond small-scale changes as shown by current pilots and early MaaS schemes. More studies in both commercial and trial settings are needed before we can reach a consensus on whether, and if so, how MaaS can achieve societal goals, such as reducing traffic congestion and CO_2 emissions in a meaningful way. It is certain that such objective is more likely to be reached if MaaS is integrated into a larger set of environmental and transport policies that favor the use of public transport and active modes, restricting the use of single-occupancy cars (Buehler et al., 2017). This open question is inseparable from the issue of how to scale up MaaS, i.e., if it can become a mainstream product (cf. a niche market) so that a seemingly small environmental benefit at the individual level sums up to a significant benefit at the city/society level.

Second, the collective evidence obtained from the UbiGo and Sydney MaaS trials (Smith et al., Sochor et al., 2016; Sochor et al., 2015; Ho et al., 2021a; Hensher et al., 2021a; Ho, 2022) and SP studies (Ho et al., 2018, 2021b) suggests that despite the convenience and innovative solution a smart app could offer to MaaS users, a MaaS app alone does not have a meaningful effect on decarbonization through changing its users' travel behavior towards more sustainable choices. Appropriate levels of incentive should be built into the MaaS offers so that users can see the benefits of using MaaS, in the presence of existing free smart apps that can offer multimodal journey planning and/or ticketing and payment features. In a way, this is yet another proof of what we knew already: people need real incentives to adopt a more sustainable mobility pattern, and the addition of a digital platform to the suite of transport policy tools does not change this simple truth.

To date, there exists no comprehensive study that fully assesses all costs and benefits of MaaS. Like any investment in the transport sector, the direct costs of developing and implementing MaaS are easier to quantify than the benefits and the external costs it may bring. At the high level, costs include development costs (associated with developing a digital platform for MaaS app, maintaining it, and improving the products along the way), costs of incentivizing MaaS users through, for example, providing financial discounts, administration costs and operation cost (data storage and analysis, product design, marketing, etc.). Many potential benefits of MaaS, however, remain unproven due to the very few trials and commercial offers of MaaS that are also limited in scope (number of users) and spatial coverage. The crucial question around the scalability of MaaS is still outstanding for the quantification of MaaS benefits.

5. Estimation of energy requirements and CO_2 emissions

5.1. Background: life-cycle assessment

In this section, we provide an estimation of energy requirements and CO_2 emissions of different transport modes, in order to have a glimpse at the marginal effect of modal shifts that may be induced by well-designed MaaS products. Our estimation considers the full life cycle of each travel alternative. A Life Cycle Assessment (LCA) evaluates energy use and environmental impacts of a product or a service, taking into account all contributions enabling its existence, use and disposal (OECD/ITF, 2020; Chester and Horvath, 2009). By setting a common framework, LCA is well suited to compare the environmental effect of different products or services that fulfill the same purpose (Klöpffer, 2014), for example, alternative modes to perform trips. In the case of travel modes, LCA includes vehicle manufacturing and maintenance, transport from the point of manufacture to the point of use, active vehicle operation, inactive vehicle operation, infrastructure (construction, operation and maintenance), fuel or energy production and vehicle and infrastructure end-of-life treatment. The LCA has been recently expanded to include internal combustion engine vehicles, electric vehicles and shared-mobility platforms based on cars, bicycles, electric bicycles and electric scooters (OECD/ITF, 2020) and to estimate changes in carbon emissions by persons who change the mode of transport for different travel purposes (Brand et al., 2021). OECD/ITF (2020) shows how the inclusion of deadheading[11] (empty vehicles between the end of one trip and the beginning of the next one) significantly adds to the carbon footprint of ridesourcing platforms, which echoes previous results on the effect of ridesourcing' empty kilometers and modal substitution from public transport as the two major forces behind an estimated increase in motorized traffic due to ridesourcing (Henao and Marshall, 2019; Tirachini and Gomez-Lobo, 2020).

In transport, LCA has been made in high-income countries (e.g., Chester and Horvath, 2009; Chester et al., 2010) or using a mix of data from high-income countries in Europe and North America, plus "average world conditions" (OECD/ITF, 2020). We depart from these research efforts by applying the LCA method to travel modes of a large city from a developing country, Santiago in Chile. As a second extension to previous transport LCA estimations, we also include intermodal alternatives, by simulating a traveler that uses a shared-mobility service (shared e-scooter, shared bicycle or ridesourcing) in combination with Metro (subway). Intermodal alternatives are included in our analysis given their relevance for the design and sustainability analysis of MaaS schemes.

5.2. Input data

We now explain the sources and assumptions for the local input data used and assumptions made in cases where local data were not available. Public transport occupancy comes from SECTRA (2013) and the Metro company for public transport, SECTRA (2013) for private cars (1.46 pax/veh) and Tirachini and del Río (2019) for ridesourcing (1.5 pax/veh while in service). For ridesourcing, deadheading (empty kilometers) is estimated as 34.5% of the total vehicle distance, which is the central value based on Tirachini and Gomez-Lobo (2020). In the case of intermodal trips, it was assumed that 12% of the trip length is performed in the access mode, an estimation based on SECTRA (2014). For electric vehicles (scooters, bicycles, cars, buses and Metro), the current electricity generation mix for Chile is used, which is 38% coal, 19% hydroelectric, 18% natural gas, 11% solar, 8% wind, 3% biomass, and 3% residual oil (García Bernal, 2021). Due to lack of local data, the following parameters are taken from OECD/ITF (2020): vehicle lifetime,[12] emissions and energy consumption due to vehicle manufacturing, fuel and electricity use efficiency, energy intensity of fuel production and electricity production, and emissions and energy requirements for infrastructure production.

For the estimation of transport emissions from the place of manufacturing to Chile, we use the current split of the country of origin for the case of cars (24.7% China, 10.3% South Korea, 10.2% India, 8.8% Japan, 7.9% Brazil, 7.5% Mexico, 6.6% Thailand, 5.9% France, 4.6% Argentina, 13.5% others), plus the most common origin in the case of conventional diesel buses (Brazil), electric buses (China), shared bicycles and shared scooters (China). Most vehicles enter Chile through the San Antonio Port and the shipping distance from port to port is considered. The emissions due to transport to Chile in container ships is added to the emissions from vehicle manufacturing, although it turns out to be a very minor contributor relative to vehicle manufacturing and vehicle use. Emissions due to vehicle disposal at the end of the life cycle are not considered. The resulting set of input parameters is shown in the Appendix. Results are shown in Fig. 3 for carbon emissions (CO_2 equivalent) per passenger-kilometer traveled (PKT) and in Fig. 4 for energy requirements (Mega-Joules MJ) per PKT.

5.3. Discussion

Figs. 3 and 4 provide several insights for analysis. The most environmentally friendly travel alternatives are private bikes (including e-bikes) and Metro, followed by shared bicycles, buses and shared e-scooters. These are a combination of modes that cater short distance (bicycles) and long distance (public transport). The private car is, as expected, a large polluter, with electric cars partially reducing carbon emissions (as currently 41% of electricity is generated with renewable energy sources). Regarding propulsion technology, the comparison of electric versus internal combustion engine (ICE) vehicles shows that electric vehicles pollute less during operation but more during manufacturing (OECD/ITF, 2020). Finally, the most polluting option is ridesourcing, even when the vehicles used to provide the services are electric. The main difference between private cars and ridesourcing in this simulation is the existence of deadheading for ridesourcing, which significantly increases vehicle kilometers. An advantage of ridesourcing over private cars is that ridesourcing does not require parking (beyond the necessary time to pick-up and drop-off passengers), the extra need for parking is indeed accounted for private cars in Figs. 3 and 4.

Figs. 3 and 4 show that even though intermodal trips increase carbon emissions and energy consumption over pure Metro trips, the increase is minor, such that these intermodal alternatives are still clearly more environmentally friendly than traveling fully by private car or ridesourcing. Finally, when comparing our results with those of OECD/ITF (2020), we can find a general agreement in the tendencies, with the main difference being that in our Santiago case the emission and energy consumption outputs of the public transport modes are relatively lower, compared to the other modes, than the estimations from OECD/ITF (2020). This is because in OECD/ITF (2020) average occupancies from London were used for buses (17 pax/bus) and Metro trains (190 pax/-train), whereas we estimate average occupancies for buses to be 25.5, 21.1 and 29.9 pax/bus in average, off-peak and peak conditions,

[11] Deadheading, also known as dead-running, happens when a revenue-gaining vehicle operates without carrying or accepting passengers, such as when coming from a depot/driver's home to begin its first trip of the day, or from the last drop-off point to the current pick-up point.

[12] Vehicle lifetime is taken from OECD/ITF (2020), except for the case of buses, in which a local estimation is available (around 850.000 km, taken from Tirachini and Antoniou, 2020), which is larger than the original value from OECD/ITF (2020). For the case of ridesourcing, the lifetime used by Tirachini and Antoniou (2020) and OECD/ITF (2020) are roughly similar, around 300.000 km.

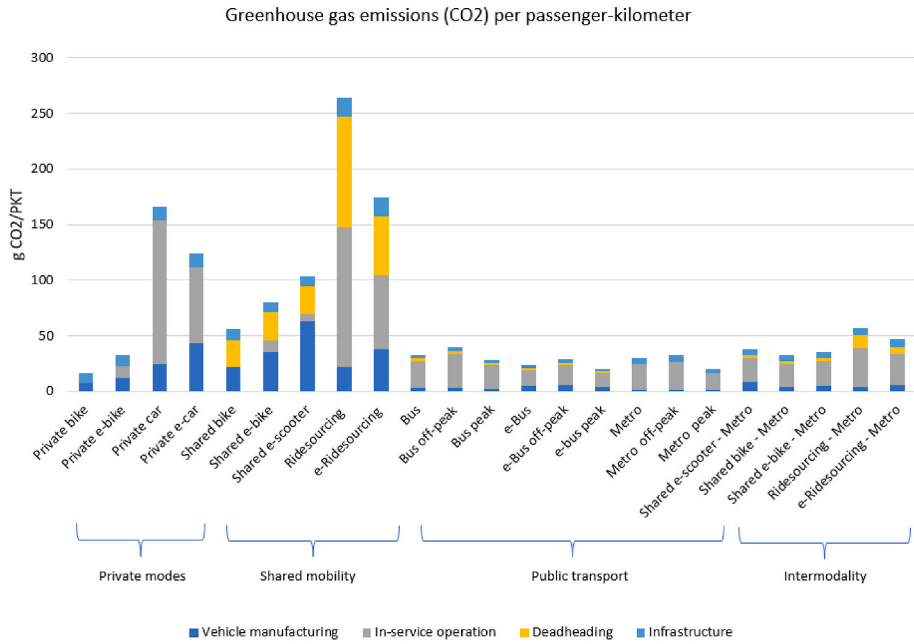

Fig. 3. CO_2-equivalent emissions per passenger-kilometer.

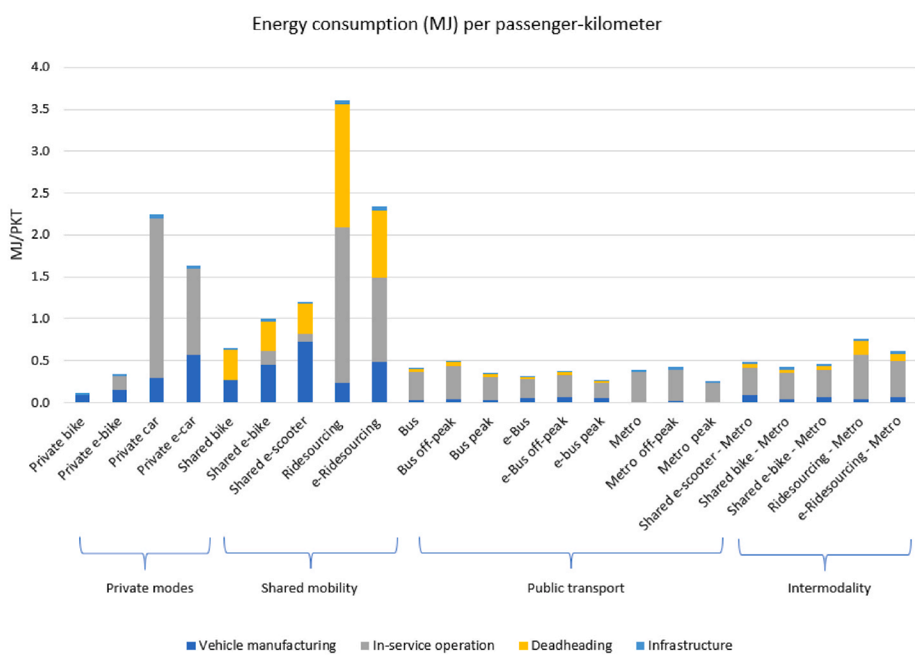

Fig. 4. Energy consumption per passenger-kilometer.

respectively, and for Metro trains to be 400, 369 and 604 pax/train in average, off-peak and peak conditions, respectively (pre COVID-19 pandemic conditions). Therefore, the more intensive use of public transport drives the Santiago results in Figs. 3 and 4.

Estimating the carbon footprint of current travel patterns in the city shown in Fig. 3 is challenging. This is because the latest Origin-Destination survey in Santiago was performed in 2012–2013 (SECTRA, 2014), before modes like bike-sharing and ridesourcing were widely available. We resort to the travel survey made by Astroza et al. (2020) in which an online sample of 3222 respondents in Santiago

Table 2
Estimation of carbon footprint of the existing travel patterns in Santiago.

Mode	Trip stages per week		Modal share (trip stages)	Trip length [km]	In-service emissions [kg CO_2]	LCA emissions [kg CO_2]	Share in-service CO_2 emissions	Share LCA CO_2 emissions
	Total	Per person						
Car	13,914	4.3	25.3%	8.3	14,906	19,334	58.9%	53.6%
Bus	16,697	5.2	30.3%	8.0	3288	4344	13.0%	12.1%
Metro	15,734	4.9	28.6%	9.1	3347	4238	13.2%	11.8%
Ridesourcing	4708	1.5	8.6%	6.4	3785	7971	14.9%	22.1%
Bicycle	3987	1.2	7.2%	2.3	0	153	0.0%	0.4%
Total	71,217	22.1	100%		25,327	36,040	100%	100%

reported all trips performed per mode, for a full week in March20, 20.[13] In Table 2 we show the total number of trips using each mode from Astroza et al. (2020), disregarding modes like motorcycles and taxis (which are not included in the analysis of Figs. 3 and 4). Trip lengths are taken from SECTRA (2014) for all modes except ridesourcing, and from Domínguez (2023) for ridesourcing.[14] With the estimated number of trips and distances, CO_2 emissions are estimated using the results from Fig. 3, first considering in-service operation only, and secondly, including the full life-cycle analysis. We observe that 19.5% of trips using cars account for 53.6% of total LCA CO_2 emissions, whereas 6.6% of trips using ridesourcing account for 22.1% of emissions. The larger emission per pax-km of ridesourcing relative to cars (due to dead-heading) is only partially offset by the assumption of ridesourcing trips being shorter in average.

In this context, the question that we need to address is if the introduction of MaaS subscription packages would increase or reduce CO_2 emissions, and if that increase or reduction is marginal or significant. Any analysis is largely speculative at this stage. In the case of the Sydney MaaS pilot, Ho (2022) analyzed the effects on passenger-kilometers of four MaaS products that had different levels of fare discounts for public transport and car-based modes like ridesourcing. A simulation showed that the modal choice and the amount of kilometers traveled by the pilot participants depended of the subscription package design, and that, in total, there was an increase in the number of trips and kilometers by ridesourcing, and reduction in the number of trips and kilometers by private cars, whereas the total number of trips by public transport remained largely unchanged, but total trip length by public transport was reduced. These results point to the fact that MaaS products did not only influence modal choice, but also destination choice. If that is true in general, then a potential increase in vehicle kms by ridesourcing could be more than compensated by a reduction in vehicle kms by car (as it happened in the Sydney MaaS pilot, see Ho, 2022), if fewer trips are made in total and/or trips by ridesourcing are shorter than trips by private car. The Santiago exercise based on Fig. 3 and Table 2, however, shows that a replacement one-to-one of private car trips by ridesourcing trips is not enough to reduce CO_2 emissions (as the assumed increase in deadheading from ridesourcing is larger than the assumed reduction of average trip length from ridesourcing).

Next, we analyze potential savings in total life cycle CO_2 emissions that are reachable by replacing private car trips. A switch from cars to public transport produces CO_2 emission savings in the range 69%–83% if the switch is to diesel buses, 77%–88% if the switch is to electric buses, 74%–88% if the trip is performed by Metro, and 87%–90% if the trip is made by bicycle. The comparison with ridesourcing is interesting because when it replaces the private car, emissions are increased by (58%–111%) or (4%–39%) if the ridesourcing vehicle is powered by petrol or electricity, respectively; however, emissions are reduced if ridesourcing is used to access Metro, instead of for the full door-to-door trip. A replacement of a car trip by a ridesourcing-Metro trip saves CO_2 in the range 55%–72%, whereas if shared bikes are used to access Metro instead of ridesourcing, savings are 74%–80% in the case of conventional bicycles and 72%–79% in the case of electric bicycles.[15] Therefore, this analysis suggests that the only way to reduce CO_2 emissions is reducing the number of car-based trips altogether or to replace long door-to-door car-trips with multimodal journeys where ridesourcing is used to access public transport services.

In conclusion, we find that carbon-heavy car-based travel alternatives such as ridesourcing still have a role to play in sustainability-seeking MaaS developments if these low-occupancy modes are used in combination with mass public transport as feeder modes. These inter-modal trips do not significantly increase emissions per passenger kilometer if the largest part of the trip is made by mass public transport. This outcome is even more clear in developing countries if public transport is more heavily used per veh-km, as the comparison of Santiago and London shows. In any case, a full assessment of intermodal trips that include shared mobility and public transport as part of MaaS packages should include other traffic externalities such as crashes and congestion as well, as the external cost of congestion from ridesourcing is larger in peak periods in congested areas, even if used to access public transport. Regarding modal substitution, the largest CO_2 savings are reached if MaaS substitutes private car trips by public transport and active modes, for which the correct design of fare discounts in the MaaS bundles is crucial. At the same time, regarding modal substitution for door-to-door trips, at this stage it is not clear if the negative effects of a potential increase in the number of ridesourcing trips induced by MaaS can be compensated by a reduction of the number of vehicle-kilometers by private cars, as the final output depends on (i) the deadheading kilometers induced by ridesourcing, (ii) the potential reduction of average trip lengths with ridesourcing (if it happens) and (iii) the effect of MaaS on the total number of car-based trips (including private cars and shared-mobility options). More research is necessary to understand the extent to which each effect happens in reality.

6. Synthesis: policy implications and research needs on the application of MaaS in developed and developing countries

At the outset, MaaS aims to disrupt the private car ownership paradigm by providing on-demand services such that individuals would question the necessity of owning and operating their own vehicles. This leads some to believe that MaaS could solve persisting problems created

[13] We use the week of 9–15 March 2020 for this analysis, which was the last week unaffected by COVID-19 disruptions. As discussed in Astroza et al. (2020), this is a convenience sample recruited online, with a likely overrepresentation of higher-income households. Therefore, the percentage of trips per mode is only representative of the sample, however, what is generalizable is the estimated increase or reduction of the share of emissions per mode, relative to the share of trips.

[14] Domínguez (2023) estimates the average and median length of ridesourcing trips in Santiago as 6.4 and 4.7 km, respectively, based on a database of almost one million ridesourcing trips in the city.

[15] These calculations assume that 12% of the trip length is performed using the access mode in the case of intermodal trips, as explained in Section 5.2. A larger share of the trip made in the access mode would increase $C0_2$ emissions in the case of ridesourcing.

by private cars such as traffic congestion and air pollution (Narupiti, 2019). However, recent research evidence from a limited number of trials and commercial offers of MaaS in developed countries supports changes to the position of MaaS in the transport network in that MaaS should be envisioned as a supplementary service to private vehicles (Storme et al., 2020; Ho, 2022). In the developed world, private vehicles usually mean private cars, but this could be extended to include private motorcycles in developing countries (particularly in Southeast Asia cities that depend on motorcycles) where the framework for MaaS should reflect the roles of the existing modes in a multimodal future that provides more efficient and greener mobility solutions. Like private cars, the (heavy) use of private motorcycles in some developing countries creates a lot of issues relating to congestion, air pollution, traffic safety problems and noise pollution (Ngoc et al., 2021). Thus, MaaS should aim to reduce the use of these private modes with appropriate use of sticks (e.g., road pricing) and carrots (e.g., incentives) in the framework. Similarly, public transport services are typically dominated by conventional (e.g., bus) and mass public transport (e.g., heavy rail) in developed countries and some developing countries while paratransit (e.g., minibus, tuktuk, rickshaw) are popular in other developing countries. Thus, implementing MaaS in developing countries requires a re-envisioning of what MaaS is in order to properly position existing transport modes in the local market so that MaaS not only helps reduce private vehicle dependency but also allows for the maximization of otherwise underutilized public transport assets (Dzisi et al., 2022).

If the scalability of MaaS beyond niche markets is a big question in rich countries, it is more so in developing economies given all the institutional and financial barriers faced by the transport sectors that are intrinsic of low- and middle-income countries. Several conditions need to be met in developing countries to facilitate the development of a scalable, well-functioning, equitable and green MaaS ecosystem. These include the formalization of the public transport sector, the formalization and regulation of private shared-mobility providers (e.g., ridesourcing) that might operate in grey regulatory areas, the enforcement of data sharing agreements, the application of proper pricing mechanisms that get us closer to marginal-cost pricing, and the existence of public subsidies to support the arrival of shared mobility alternatives to low-income areas that are avoided by private for-profit shared-mobility providers. We have also emphasized that the formalization of public transport and shared-mobility providers requires the formalization of the job of drivers.

Beyond the open question about scalability, the early results about the MaaS effects on decarbonization that have been found in high-income countries (Section 4), either in empirical studies of real MaaS platforms (Hensher et al., 2021a) or based on city-wide simulations (Becker et al., 2020), certainly are not directly translated to the potential application of MaaS in developing countries whose transport networks are characterized by lower car ownership rates and, in several cases, an informal public transport sector and a decreasing trend in the modal share of public transport (Section 3). For cities with poor quality of public transport services, it is recommended that resources should be focused on improving public transport services because public transport should be the backbone of MaaS if the objective is to decarbonize the transport sectors through an affordable and scalable MaaS. Put it differently, introducing MaaS products in a market where public transport service is poor (e.g., limited spatial coverage, low quality of vehicles, unreliable services and/or low frequency) necessitates a reliance on other shared modes such as ridesourcing, taxi or paratransit. While such a MaaS scheme may be profitable, it will not help decarbonize the transport sector because, as illustrated in Section 5, most shared modes are still car-based and hence, carbon-heavy. Also, a reduction in the use of private car modes may be offset by an increased use of car-based shared modes (Smith et al.; Ho, 2022). Leaning too much on ridesourcing and ride-sharing services to make MaaS work is dangerous because there is little motivation for the private providers to reduce transport emissions. This raises an important governance issue in that appropriate regulations need to be introduced to prevent a potential danger of MaaS being developed solely for profitability purposes, with little or no consideration for environmental sustainability.

Our exercise on the carbon emissions and energy requirements of different transport alternatives in a developing country, using Santiago in Chile for illustration (Section 5) quantifies that a low-carbon future depends on the use of active modes for short trips, plus public transport and intermodal modes for long trips. Car-based alternatives such as ridesourcing still have an important role to play in that future if combined with mass public transport to enlarge the catchment area of rail and/or BRT stations, i.e., as a first-mile or last-mile mode. This is because car-based modes, while carbon-heavy, are used to access environmentally friendly mass public transport services, which does not substantially increase emissions per passenger kilometer, provided that the largest part of the trip is made by mass public transport. This is even more significant in developing countries if public transport is used more heavily, as the comparison of Santiago and London in Section 5 showed. This symbiotic relationship between public transport and a shared bicycle, shared car or ridesourcing, can be encouraged with well-designed MaaS instruments. Such an outcome unavoidably requires the involvement of the public sector in the design and regulation of the MaaS developments. As said, we therefore cannot escape the conclusion that governance, regulation, the setting of the right objectives and financial backing are a prerequisite for the proper functioning of any MaaS scheme, either in developing or developed countries.

As with other studies, this work has limitations. First and foremost, we recognized the importance of having a plan for MaaS implementation; however, such a plan must consider the characteristics of the context, which is unique to each country and/or city, as discussed in Section 3.1. Thus, in this paper, we only discussed the broader and general issues relating to implementation (e.g., barriers, indicative costs, and social inequity) without suggesting a specific roadmap for implementing MaaS in developing countries. Interested readers are referred to Nelson et al. (2023) who discuss at length the ten steps of the implementation roadmap, from defining MaaS vision to scaling it up.

Author statement

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Data availability

Data will be made available on request.

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Appendix

Values used for the Life Cycle Assessment

	Private bike	Private e-bike	Private car	Private e-car	Shared bike	Shared e-bike	Shared e-scooter	Ridesourcing	e-Ridesourcing	Bus	e-Bus	Metro
Lifetime [years]	5.6	5.6	15	15	1.9	1.9	2	7.1	7.1	12	12	40
Annual Km	2400	2400	12,100	12,100	2900	2900	2900	48,000	48,000	71,333	71,333	66,000
Lifetime [km]	13,440	13,440	181,500	181,500	5510	5510	5703	340,358	340,358	856,000	856,000	2640000
Energy consumption veh manufacturing [MJ/veh]	1159	2028	78,371	150,674	1484	2464	4146	78,382	163,399	650,735	1143254	12431908
CO2 emissions veh manufacturing [kg CO2 eq/veh]	90	154	6357	11,170	114	188	356	7075	12,279	52,977	91,085	1003085
Energy consumption transport [MJ/veh]	39	53	2156	2617	53	62	57	2156	2718	7072	24,321	236,861
CO2 emissions transport [kg CO2 eq/veh]	4	5	203	247	5	6	5	203	256	677	2289	21,967
Energy consumption in-service [MJ/veh]	0	2230	504,948	272,953	0	914	536	946,905	511,856	6501310	4298816	369625420
CO2 emissions in-service [kg CO2 eq/veh]	0	149	34,203	18,232	0	61	36	64,140	34,189	483,597	287,134	24688703
Energy consumption deadheading [MJ/veh]	0	0	0	0	1964	1964	2033	165,928	89,693	722,368	477,646	0
CO2 emissions deadheading [kg CO2 eq/veh]	0	0	0	0	136	136	141	11,239	5991	53,733	31,904	0
Energy consumption infrastructure [MJ/vkm]	0	0	0	0	0	0	0	0	0	0	0	11
CO2 emissions infrastructure [g CO2 eq/vkm]	9	9	19	18	9	10	9	16	16	55	60	2091
Occupancy rate average [pax/veh]	1	1	1.46	1.46	1	1	1	1.5	1.5	23	23	400
Occupancy rate off-peak [pax/veh]	1	1	1.46	1.46	1	1	1	1.5	1.5	19	19	369
Occupancy rate peak [pax/veh]	1	1	1.46	1.46	1	1	1	1.5	1.5	27	27	604

Source: the authors, using sources described in Section 5

References

Aapaoja, A., Eckhardt, J., 2017. Business Models for MaaS. *1st International Conference On Mobility As a Service*. Tampere. November 2017.

Acheampong, R.A., 2021. Societal impacts of smart, digital platform mobility services—an empirical study and policy implications of passenger safety and security in ride-hailing. Case Studies on Transport Policy 9, 302–314.

Acheampong, R.A., Siiba, A., 2020. Modelling the determinants of car-sharing adoption intentions among young adults: the role of attitude, perceived benefits, travel expectations and socio-demographic factors. Transportation 47, 2557–2580.

Alonso-González, M.J., Hoogendoorn-Lanser, S., van Oort, N., Cats, O., Hoogendoorn, S., 2020. Drivers and barriers in adopting Mobility as a Service (MaaS) – a latent class cluster analysis of attitudes. Transport. Res. Pol. Pract. 132, 378–401.

Astroza, S., Tirachini, A., Hurtubia, R., Carrasco, J.A., Guevara, A., Munizaga, M., Figueroa, M., Torres, V., 2020. Mobility changes, teleworking, and remote communication during the Coronavirus COVID-19 pandemic in Chile. Transport Findings. https://doi.org/10.32866/001c.13489.

Becker, H., Balac, M., Ciari, F., Axhausen, K.W., 2020. Assessing the welfare impacts of shared mobility and mobility as a service (MaaS). Transport. Res. Pol. Pract. 131, 228–243.

Becker, U.J., Becker, T., Gerlach, J., 2012. The true costs of automobility: external costs of cars overview on existing estimates in EU-27. In: Report, Chair of Transport Ecology. TU Dresden.

Brand, C., Götschi, T., Dons, E., Gerike, R., Anaya-Boig, E., Avila-Palencia, I., de Nazelle, A., Gascon, M., Gaupp-Berghausen, M., Iacorossi, F., Kahlmeier, S., Int Panis, L., Racioppi, F., Rojas-Rueda, D., Standaert, A., Stigell, E., Sulikova, S., Wegener, S., Nieuwenhuijsen, M.J., 2021. The climate change mitigation impacts of active travel: evidence from a longitudinal panel study in seven European cities. Global Environ. Change 67, 102224.

Buehler, R., Pucher, J., Gerike, R., Götschi, T., 2017. Reducing car dependence in the heart of Europe: lessons from Germany, Austria, and Switzerland. Transport Rev. 37, 4–28.

Butler, L., Yigitcanlar, T., Paz, A., 2021. Barriers and risks of Mobility-as-a-Service (MaaS) adoption in cities: a systematic review of the literature. Cities 109, 103036.
Caiati, V., Rasouli, S., Timmermans, H., 2018. Subscription and bundling preferences for mobility as a service: a sequential portfolio choice experiment. In: Transportation Systems in the Connected Era: Proceedings of the 23rd International Conference of Hong Kong Society for Transportation Studies (HKSTS), 683-391.
Caiati, V., Rasouli, S., Timmermans, H., 2020. Bundling, pricing schemes and extra features preferences for mobility as a service: sequential portfolio choice experiment. Transport. Res. Pol. Pract. 131, 123–148.
Chester, M., Horvath, A., Madanat, S., 2010. Parking infrastructure: energy, emissions, and automobile life-cycle environmental accounting. Environ. Res. Lett. 5, 034001.
Chester, M.V., Horvath, A., 2009. Environmental assessment of passenger transportation should include infrastructure and supply chains. Environ. Res. Lett. 4, 024008.
Conway, W.M., Salon, D., King, A.D., 2018. Trends in Taxi Use and the Advent of Ridehailing, 1995–2017: Evidence from the US National Household Travel Survey, vol. 2. Urban Science.
Domínguez, B., 2023. Modelación y análisis espacio-temporal de la demanda de viajes en ridesourcing en Santiago de Chile. MSc Thesis, Universidad de Chile.
Dzisi, E.K.J., Obeng, D.A., Ackaah, W., Tuffour, Y.A., 2022. MaaS for paratransit minibus taxis in developing countries: a review. Travel Behaviour and Society 26, 18–27.
Fielbaum, A., Ruiz, F., Boccardo, G., Rubio, D., Tirachini, A., Rosales-Salas, J., 2023. The job of public transport, ride-hailing and delivery drivers: conditions during the COVID-19 pandemic and implications for a post-pandemic future. Travel Behaviour and Society 31, 63–77.
Fielbaum, A., Tirachini, A., 2021. The sharing economy and the job market: the case of ride-hailing drivers in Chile. Transportation 48, 2235–2261.
Gakenheimer, R., 1999. Urban mobility in the developing world. Transport. Res. Part A 33, 671–689.
Gandia, R.M., 2021. MaaS as a catalyst for the public transport revolution in developing countries. In: The Robomobility Revolution of Urban Public Transport. Springer.
Gandia, R.M., Antonialli, F., Oliveira, J.R., Sugano, J.Y., Nicolaï, I., Oliveira, I.R.C., 2021. Willingness to use MaaS in a developing country. International journal of transport development and integration 5, 57–68.
García Bernal, N., 2021. Matriz energética y eléctrica en Chile. Biblioteca del Congreso Nacional de Chile, Asesoría Técnica Parlamentaria.
Geurs, K.T., La Paix, L., Van Weperen, S., 2016. A multi-modal network approach to model public transport accessibility impacts of bicycle-train integration policies. European transport research review 8, 25.
Guidon, S., Wicki, M., Bernauer, T., Axhausen, K., 2019. Transportation service bundling – for whose benefit?. In: Consumer Valuation of Pure Bundling in the Passenger Transportation Market. Transportation Research Part A: Policy and Practice.
Gwilliam, K., 1999. Public transport in the developing world, quo vadis?. In: International Conference Series on Competition and Ownership in Land Passenger Transport- Thredbo, vol. 6 Cape Town, South Africa.
Henao, A., Marshall, W.E., 2019. The impact of ride-hailing on vehicle miles traveled. Transportation 46, 2173–2194.
Hensher, D.A., Ho, C.Q., Mulley, C., Nelson, J.D., Smith, G., Wong, Y.Z., 2020. Understanding Mobility as a Service (MaaS): Past, Present and Future. Elsevier.
Hensher, D.A., Ho, C.Q., Reck, D.J., 2021a. Mobility as a service and private car use: evidence from the Sydney MaaS trial. Transport. Res. Pol. Pract. 145, 17–33.
Hensher, D.A., Mulley, C., Nelson, J.D., 2021b. Mobility as a Service (MaaS) – Going Somewhere or Nowhere? *Institute of Transport And Logistics Studies (ITLS) Working Paper Series*. The University of Sydney, Australia.
Hidalgo, D., Huizenga, C., 2013. Implementation of sustainable urban transport in Latin America. Res. Transport. Econ. 40, 66–77.
Ho, C.Q., 2022. Can MaaS change users' travel behaviour to deliver commercial and societal outcomes? Transport. Res. Pol. Pract. 165, 76–97.
Ho, C.Q., Hensher, D.A., Mulley, C., Wong, Y.Z., 2018. Potential uptake and willingness-to-pay for Mobility as a Service (MaaS): a stated choice study. Transport. Res. Pol. Pract. 117, 302–318.
Ho, C.Q., Hensher, D.A., Reck, D.J., 2021a. Drivers of participant's choices of monthly mobility bundles: key behavioural findings from the Sydney Mobility as a Service (MaaS) trial. Transport. Res. C Emerg. Technol. 124, 102932.
Ho, C.Q., Hensher, D.A., Reck, D.J., Lorimer, S., Lu, I., 2021b. MaaS bundle design and implementation: lessons from the Sydney MaaS trial. Transport. Res. Pol. Pract. 149, 339–376.
Ho, C.Q., Mulley, C., Hensher, D.A., 2020. Public preferences for mobility as a service: insights from stated preference surveys. Transport. Res. Pol. Pract. 131, 70–90.
Hörcher, D., Graham, D.J., 2020. MaaS economics: should we fight car ownership with subscriptions to alternative modes? Economics of Transportation 22, 100167.
Hörcher, D., Tirachini, A., 2021. A review of public transport economics. Economics of Transportation 25, 100196.
Horni, A., Nagel, K., Axhausen, K.W., 2016. The Multi-Agent Transport Simulation MATSim. Ubiquity Press, London. https://doi.org/10.5334/baw.84. License: CC-BY4.0.
IPCC, 2021. Climate Change 2021: the Physical Science Basis. *Working Group I Contribution to the Sixth Assessment Report Of the Intergovernmental Panel On Climate Change (IPCC)*.
Jittrapirom, P., Caiati, V., Feneri, A.-M., Ebrahimigharehbaghi, S., González, M.J.A., Narayan, J., 2017. Mobility as a service: a critical review of definitions, assessments of schemes, 2017 and Key Challenges 2, 13.
Kager, R., Bertolini, L., Te Brömmelstroet, M., 2016. Characterisation of and reflections on the synergy of bicycles and public transport. Transport. Res. Pol. Pract. 85, 208–219.
Kamargianni, M., Matyas, M., Li, W., Muscat, J., Yfantis, L., 2018. The MaaS Dictionary. MaaSLab, Energy Institute, University College London. *Available at:*. www.maaslab.org.
Klöpffer, W., 2014. Introducing life cycle assessment and its presentation in 'LCA compendium'. In: Klöpffer, W., Curran, M.A. (Eds.), LCA Compendium - the Complete World of Life Cycle Assessment. Springer.
Korzhenevych, A., Dehnen, N., Bröcker, J., Holtkamp, M., Meier, H., Gibson, G., Varma, A., Cox, V., 2014. Update of the Handbook on External Costs of Transport. Final Report, European Commission.
Kuhnimhof, T., Chlond, B., Huang, P.-C., 2010. Multimodal travel choices of bicyclists: multiday data analysis of bicycle use in Germany. Transport. Res. Rec. 2190, 19–27.
Lyons, G., Hammond, P., Mackay, K., 2019. The importance of user perspective in the evolution of MaaS. Transport. Res. Pol. Pract. 121, 22–36.
Matyas, M., Kamargianni, M., 2019. The potential of mobility as a service bundles as a mobility management tool. Transportation 46, 1951–1968.
McFadden, E. 17/03/2021 2021. RE: MaaS Project Knowledge Share (Sydney & Minnesota DOT). Type to HO, C. Q..
Mora, R., Moran, P., 2020. Public bike sharing programs under the prism of urban planning officials: the case of Santiago De Chile. Sustainability 12, 5720.
Mueller, N., Rojas-Rueda, D., Cole-Hunter, T., de Nazelle, A., Dons, E., Gerike, R., Götschi, T., Int Panis, L., Kahlmeier, S., Nieuwenhuijsen, M., 2015. Health impact assessment of active transportation: a systematic review. Prev. Med. 76, 103–114.
Narupiti, S., 2019. Exploring the possibility of MaaS service in Thailand, implications from the existing conditions and experts' opinions on "Who should be the MaaS provider in Bangkok?". IATSS Res. 43, 226–234.
Nelson, J.D., Mulley, C., Hensher, D.A., Ho, C., Xi, H., Balbontin, C., 2023. The MaaS Blueprint for Regional Towns and Rural Hinterlands. Institute of Transport and Logistics Studies, The University of Sydney, Australia.
Ngoc, A.M., Nishiuchi, H., Van Truong, N., Huyen, L.T., 2021. A comparative study on travel mode share, emission, and safety in five Vietnamese Cities. International Journal of Intelligent Transportation Systems Research. 20, 157–169.
OECD/ITF, 2020. Good to go? Assessing the environmental performance of new mobility. Corporate Partnership Board Report, International Transport Forum.
Pangbourne, K., Mladenović, M.N., Stead, D., Milakis, D., 2020. Questioning mobility as a service: unanticipated implications for society and governance. Transport. Res. Pol. Pract. 131, 35–49.
Parry, I.W.H., Small, K.A., 2009. Should urban transit subsidies be reduced? Am. Econ. Rev. 99, 700–724.
Parry, I.W.H., Timilsina, G.R., 2010. How should passenger travel in Mexico City be priced? J. Urban Econ. 68, 167–182.
Phillips, T., 2021. Sydney integrates digital Opal card with rideshare services. Sydney Morning Herald [Online]. Available: https://www.nfcw.com/2021/03/31/371455/sydney-integrates-digital-opal-card-with-rideshare-services/.
Rautavirta, M., Kaivola, T., 2018. In: COMMUNICATIONS, M.O.T.A. (Ed.), Finnish Policy – State of Play.
Reck, D.J., Axhausen, K.W., 2020. How much of which mode? Using revealed preference data to design mobility as a service plans. Transport. Res. Rec. 2674, 494–503.
Reck, D.J., Axhausen, K.W., Hensher, D.A., Ho, C.Q., 2021. Multimodal Transportation Plans: Empirical Evidence on Uptake, Usage and Behavioral Implications from the Augsburg MaaS Trial. 100th Annual Meeting of the Transportation Research Board, Washington D.C.
SAE International, 2021. Taxonomy of on-demand and shared mobility: ground, aviation, and marine. JA3163_202106. Available at: https://webstore.ansi.org/standards/sae/saeja31632021.
Santos, G., Behrendt, H., Maconi, L., Shirvani, T., Teytelboym, A., 2010. Part I: externalities and economic policies in road transport. Res. Transport. Econ. 28, 2–45.
SECTRA, 2013. Mediciones de aforos de tráfico y perfiles de carga en servicios troncales en el Gran Santiago. *Report prepared by DICTUC*.
SECTRA, 2014. Encuesta de Origen y Destino de Viajes Santiago 2012 (in Spanish). *Report and database available at*: www.sectra.gob.cl.
Sgarro, V., 2018. What are "Ethics in design"? [Online]. Slate. Available: https://slate.com/technology/2018/08/ethics-in-design-what-exactly-does-that-mean.html. (Accessed 20 April 2021).
Sikder, S., 2019. Who Uses Ride-Hailing Services in the United States? *Transportation Research Record*, 0361198119859302.
Sims, R., Schaeffer, R., Creutzig, F., Cruz-Núñez, X., D'Agosto, M., Dimitriu, D., Figueroa Meza, M.J., Fulton, L., Kobayashi, S., Lah, O., McKinnon, A., Newman, P., Ouyang, M., Schauer, J.J., Sperling, D., Tiwari, G., 2014. Transport. *Climate Change 2014: Mitigation Of Climate Change. Contribution Of Working Group III to the Fifth Assessment Report Of the Intergovernmental Panel On Climate Change*.
Smith, G., Sochor, J., Karlsson, I.C.M., 2021. Adopting Mobility-As-A-Service: an Empirical Analysis of End-Users' Experiences. Revised paper submitted to Travel Behaviour and Society.
Smith, G., Sochor, J. & Karlsson, M. Adopting Mobility-as-a-Service: an empirical analysis of end-users' experiences. The 2nd International Conference on Mobility as a Service 3-4/12/2019 2019 Tampere, Finland.
Sochor, J., Arby, H., Karlsson, I.C.M., Sarasini, S., 2018. A topological approach to Mobility as a Service: a proposed tool for understanding requirements and effects, and for aiding the integration of societal goals. Research in Transportation Business & Management 27, 3–14.
Sochor, J., Karlsson, I.C.M., Strömberg, H., 2016. Trying out mobility as a service: experiences from a field trial and implications for understanding demand. Transport. Res. Rec. 2542, 57–64.
Sochor, J., Strömberg, H., Karlsson, I.C.M., 2015. Implementing mobility as a service: challenges in integrating user, commercial, and societal perspectives. Transport. Res. Rec. 2536, 1–9.

Storme, T., De Vos, J., De Paepe, L., Witlox, F., 2020. Limitations to the car-substitution effect of MaaS. Findings from a Belgian pilot study. Transport. Res. Pol. Pract. 131, 196–205.
Strömberg, H., Karlsson, I.C.M., Sochor, J., 2018. Inviting travelers to the smorgasbord of sustainable urban transport: evidence from a MaaS field trial. Transportation 45, 1655–1670.
Tirachini, A., 2019. South America: the challenge of transition. In: Stanley, J., Hensher, D. (Eds.), A Research Agenda for Transport Policy. Edward Elgar Publishing. https://doi.org/10.4337/9781788970204.00023.
Tirachini, A., 2020. Ride-hailing, travel behaviour and sustainable mobility: an international review. Transportation 47, 2011–2047.
Tirachini, A., Antoniou, C., 2020. The economics of automated public transport: effects on operator cost, travel time, fare and subsidy. Economics of Transportation 21, 100151.
Tirachini, A., del Río, M., 2019. Ride-hailing in Santiago de Chile: users' characterisation and effects on travel behaviour. Transport Pol. 82, 46–57.
Tirachini, A., Gomez-Lobo, A., 2020. Does ride-hailing increase or decrease vehicle kilometers traveled (VKT)? A simulation approach for Santiago de Chile. International Journal of Sustainable Transportation 14 (3), 187–204.
Tirachini, A., Proost, S., 2021. Transport taxes and subsidies in developing countries: the effect of income inequality aversion. Economics of Transportation 25, 100206.
Veeneman, W., 2019. Chapter Three - public transport in a sharing environment. In: FISHMAN, E. (Ed.), Advances in Transport Policy and Planning. Academic Press.
Walters, J., Pisa, N., 2022. Review of South Africa's public transport system'S SUB-optimal performance. In: The 17th International Conference Series on Competition and Ownership in Land Passenger Transport Conference (Thredbo). Sydney Australian.
Wong, Y.Z., Hensher, D.A., 2021. Delivering mobility as a service (MaaS) through a broker/aggregator business model. Transportation 48, 1837–1863.
Wong, Y.Z., Hensher, D.A., Mulley, C., 2020. Mobility as a service (MaaS): charting a future context. Transport. Res. Pol. Pract. 131, 5–19.
Young, M., Farber, S., 2019. The who, why, and when of Uber and other ride-hailing trips: an examination of a large sample household travel survey. Transport. Res. Pol. Pract. 119, 383–392.
Zijlstra, T., Durand, A., Hoogendoorn-Lanser, S., Harms, L., 2020. Early adopters of mobility-as-a-service in The Netherlands. Transport Pol. 97, 197–209.