Emerging transport technologies and the modal efficiency framework: A case for mobility as a service (MaaS)

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ABSTRACT

The land passenger transport sector lies on the cusp of a major transformation, guided by collaborative consumption, next generation vehicles, demographic change and digital technologies. Whilst there is widespread enthusiasm across the community for this nexus of disruptors, the wholescale implications on road capacity, traffic congestion, land use and the urban form remains unclear, and by extension, whether this emerging transport paradigm will bring a net benefit to the transport system and our communities. Some issues include the proliferation of point-to-point transportation, a continuation of universal vehicle ownership, and the demise of fixed route public transport—all envisaged by various industry leaders in technology and transportation. In this paper, we develop the *modal efficiency framework*, with axes representing spatial and temporal efficiency to illustrate why some of these developments may be geometrically incompatible with dense urban environments. We then investigate three potential scenarios likely to emerge and explain why they may be problematic with reference to this framework. Mobility as a service (MaaS) based on shared mobility and modal integration is then introduced as a sustainable alternative which accounts for the realities of spatial and temporal efficiency. Various models for implementing MaaS are evaluated including the distinction between commercially-motivated models (presently well advanced in research and development), and systems which incorporate an institutional overlay. The latter, government-led MaaS, is recommended for implementation given the opportunity for incorporating road pricing as an input into package price, defined by time of day, geography and modal efficiency. In amidst the hype of this emerging transport paradigm, a critical assessment of the realm of possibilities can better inform government policy and ensure that digital disruption occurs to our advantage.

1. Introduction

Cities, in bringing people and activities together, are an attempted solution to the transportation problem—reaping economies of scale from the shared use of infrastructure and services. This is built around sufficient population and employment *d*ensities, land use *d*iversity and transit-conducive urban *d*esign—the oft-cited *three Ds* proposed in the classic paper Cervero and Kockelman (1997). Ewing and Cervero (2010) extended these variables to include *d*estination accessibility, *d*istance to transit, *d*emand management and *d*emographics (as a confounding influence). Urban policy contravening these principles eventually descends into a destructive cycle, characterised by congestion and sprawl which ultimately dilutes the benefits of any agglomeration (Graham, 2007). Transportation and location choice are major inputs into the urban development process but often treated as exogenous in government policy and planning.

New transport technologies have the potential to generate unintended consequences which can compromise these ideals for sustainable cities, as demonstrated by past historical developments. For instance, the air pollution, waste products and health implications of horse-based transport were replaced by more virulent externalities as combustion-engined motor vehicles came into being (Morris, 2007). Indeed, the existing transport paradigm can be traced back to Karl Benz's Patent-Motorwagen (1885) and Henry Ford's Model T moving assembly line (1908), bringing the world (despite great benefit!) universal car ownership and oil dependence, with implications for health and land use in encouraging urban sprawl. It is therefore important not to substitute an existing transport regime with a future which compromises the fundamental underpinnings of successful and efficient cities.

The emerging transport paradigm guided by a nexus of collaborative consumption, next generation vehicles, demographic change and digital technologies has the potential to lead down a similar path. These disruptors may be regarded as a nexus because of their heavily complementary nature, but their direction of causality is generally unclear. The advent of collaborative consumption has opened up the market to intermediate modes like ridesourcing, microtransit and carsharing, courtesy of various TNC start-ups. Next generation vehicles led by autonomous and connected technologies could transform societal relationships with cars, and has implications for public transport provision by breaking the link between labour cost and service quantity. Demographic change, exhibited through a generational decline in emotional attachment towards cars, is making it more acceptable to shift from vehicle ownership to access. These trends are all underpinned by digital technologies which form the interface for connecting demanders and suppliers and facilitating the delivery of physical transportation. The implication of these future transport drivers on road capacity, traffic congestion, land use and the urban form are only just beginning to emerge and unlikely to be entirely positive, especially in the absence of strong regulation and control.

In this paper, we will explore just what kind of future these developments may bring. Sections 2-5 will discuss each of these disruptors in turn, reviewing recent literature and the latest progress from industry. Section 6 situates the plethora of new modes coming online within the *modal efficiency framework*—a tool for evaluating their spatial and temporal efficiencies and their role in a variety of urban environments. Section 7 then investigates three scenarios for modal development and implications based on this developed framework. Section 8 proposes different spatial and temporal integration opportunities to account for the varying spatial and temporal efficiency realities of each mode. Finally, Section 9 introduces the concept of mobility as a service (MaaS), including various models of implementation and proposes how these may circumvent some of the described issues associated with this emerging transport paradigm.

2. Collaborative consumption

Collaborative consumption or the sharing economy has proliferated across various sectors of the economy including hospitality (Airbnb), education (Italki), financing (Kickstarter), the labour market (TaskRabbit), property (BRICKX), in freight and passenger transportation. A multitude of application-based, shared mobility propositions have proliferated across both developed and developing countries, led (with controversy) by pioneers like Uber, Lyft, Curb, Didi Chuxing, Grab and Ola. These transportation network companies (TNCs) operate as peer-to-peer (or customer-to-customer) mutualisation schemes, challenging the traditional business-to-customer retail channel.

2.1 Ridesourcing (and carpooling)

Ridesourcing (UberX-type services also called ridehailing) has been the most prominent example of the collaborative consumption model where lower fares and a real time platform has allowed TNCs to disrupt the conventional taxi industry, with prominent impacts on the monopolistic pricing of taxi licences. Early evidence suggests that ridesourcing both competes with and complements public transport, though this depends on the exact market and demographic (Rayle, Dai, Chan, Cervero, & Shaheen, 2016). There also exists a range of commentary on the ethical implications of ridesourcing, including issues of safety, privacy discrimination and labour standards (Rogers, 2015). Looking to the future, Zha, Yin, and Yang (2016) suggest competition between TNCs do not improve social welfare in the ridesourcing market, instead encouraging platform mergers and for government to directly regulate a monopolist. Regardless of the business model, what remains to be seen is the impact of growing point-to-point transportation on road congestion, as vehicles circulate in search of trips, and passengers are drawn from more spatially efficient but less personalised public transport modes.

Unlike ridesourcing, ridesharing[1] or carpooling drivers are not motivated by fare income and usually share a destination with the passenger—part of a regular journey-to-work trip, for instance. Ridesharing has long been a popular demand management method used to improve urban efficiency by increasing the individual occupancy of private vehicles (Shaheen, 2016), which average for commuting as little as 1.2 in Australia. Digital platforms are now facilitating a new wave of ridesharing services (Chan & Shaheen, 2012), and there continues to be innovative concepts proposed or in development to further enhance ride matching capabilities (Amey, Attanucci, & Mishalani, 2011; Teubner & Flath, 2015). TNCs are also targeting this market[2] though with what appears to be less enthusiasm given the reduced margins available as the platform operator (GrabHitch and BlaBlaCar are two prominent exceptions to this). Ridesourcing continues to be their largest (and original) market, but there is increasingly an impetus to gain scale and market (from public transport) through increased sharing and larger vehicles.

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[1] Commonly incorrectly used interchangeable with ‘ridesourcing’ in both academic and popular literature.

[2] Uber’s Destination feature which matches trips towards a driver/partner-specified locality is a recent addition.

2.2 Microtransit

Microtransit has been introduced by all major players (and other startups) using everything from sedans to minivans, minibuses, midibuses and even standard rigid buses. These vehicles are either driver-owned (UberPOOL, Lyft Line, Via) or operate as part of a fleet (Bridj). Whilst early schemes operated as shared taxis (carrying few individual passengers with on demand routes and pick-up/set-up locations), the latest schemes are emulating public transport through the use of larger vehicles, fixed routes and even fixed stops. These services are indeed digitally-enabled paratransit and collectively come under the label ‘microtransit’—a term more common in the grey literature now gaining increased prominence—though others have resorted to alternative descriptors like “demand adaptive hybrid transit” (Frei, Hyland, & Mahmassani, 2017) and “point-via-point(s) to point” transport (Hensher, 2017).

A stated choice investigation of end user preferences in Frei et al. (2017) found microtransit wait time (an ‘at-home’ pick-up location) valued at USD 11.30 per hour—significantly lower than the typical disutility at bus stops, indicating the highly desired feature (and growth opportunity) of door-to-door, point-to-point transportation. There is so much interest in these concepts that even conventional public transport operators are exploring options to ‘uberise’ their services (for instance, RATP’s bookable bus service Slide Bristol). The growth of microtransit, however, poses a major threat for the survival of conventional bus operations and the existing model of remuneration for bus operators (see Section 7).

2.3 Carsharing (and cycle hire)

Another recent collaborative model for transportation is carsharing—the short-term rental of vehicles and a growing phenomenon across developed economies. These schemes may be either peer-to-peer (Car Next Door) or fleet managed, the latter run initially as return-to-base systems (GoGet), but now also as one-way and free-floating schemes (Car2Go). Carsharing has grown year-on-year in terms of members and vehicles, and expanding in geographic reach from the highest density urban centres to more marginal suburban locations (Shaheen & Cohen, 2013). Many carsharing schemes, however, remain dependent on commercial subsidies, supported by automobile manufacturers driven by their interest in bringing higher value vehicles into the market.

Whilst round-trip carsharing allows far more flexibility for users to book in advance (Zoepf & Keith, 2016), it is free-floating schemes (i.e., Car2Go-type systems) which are currently exhibiting the largest rate of growth. Such one-way schemes, however, continue to suffer from redistribution issues (as do cycle hire systems), but new concepts like the Easily diStributed Personal Rapid Transit (ESPRIT)[3] (with investment from public transport operators Keolis and First) are being developed which can couple individual vehicles (or rather, ‘pods’) to facilitate more effective operator redistribution. There is much interest here in optimising one-way distribution in urban areas and providing first/last mile transport to mass transit nodes in suburban environments. There is also a focus on the role of user incentives like free journeys to encourage users to redistribute vehicles within the system.

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[3] See http://www.esprit-transport-system.eu.

ESPRIT constitutes an early market initiative as the advent of autonomous vehicle technologies will eventually alter this paradigm significantly.

Other innovative modes of travel include cycle hire (either return-to-base or roaming) and driver-sourcing (a form of designated driver hire)—both serving more niche markets with limited availability in Australia. A new generation of dockless cycle hire has gained interest around the world since its recent proliferation across East and South-East Asia. In Australia, Melbourne has embraced Singapore's oBike[4], whilst Sydney has launched its own scheme Reddy Go[5], backed by China's Bluegogo. One major concern with deployment is in ensuring that bicycles are properly parked and that riders comply with road rules—both major issues from the Asian experience.

3. Next generation vehicles

The emerging transport paradigm is also being driven by new transport technologies—often the myopic focus of many commentators in media and government. Autonomous vehicle technologies represent the greatest transformation of the transport network since the advent of the automobile, with flow-on effects on virtually all other sectors of the economy. Recently, there are also forays into autonomous vertical take-off and landing aircraft with the view of using them for urban point-to-point transport—moving the urban passenger transport debate beyond the surface dimension.

3.1 Autonomous and connected vehicles

Autonomous and connected vehicles offer the potential for operational savings, increased road capacity, safety and social inclusion. Record investments from automobile manufacturers (Tesla, Audi), technology giants (Google, Apple) and TNCs (Uber, Didi Chuxing) are already making these technologies a reality. Debate rages, however, on the path towards autonomy, its impact on congestion and implications for car ownership. The transitional phase towards vehicle automation with autonomous and manually-driven vehicles operating in mixed traffic is particularly challenging. Whilst the safety benefits of full automation are unquestionable, with one estimate expecting traffic accidents to reduce by up to 90 percent (Bertoncello & Wee, 2015) (heralded as the greatest health achievement of the century), research has shown that semi-autonomous vehicles are likely to be more problematic[6] as drivers showed slower response times to hazards and displayed a tendency to overcompensate when any driving correction was required (Shen & Neyens, 2017).

Given these issues, there is an expanding literature on the acceptability of driverless cars, primarily through the use of stated choice techniques (Kyriakidis, Happee, & de Winter, 2015). Payre, Cestac, and Delhomme (2014), for instance, found 68 percent of respondents (n=421) willing to use autonomous vehicles, with particular interest in applications on motorway environments, in traffic congestion and for parking. Daziano, Sarrias, and Leard

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[4] See https://www.o.bike/au.

[5] See http://www.reddygo.com.au.

[6] The high-profile crash of a Tesla S on Autopilot is a case in point, and demonstrates the moral hazard issues in play.

(2017) found people's willingness-to-pay for full automation technologies at USD 4900 (n=1260). Research is also continuing on the user acceptability of automated public transport, including on heavy rail (Fraszczyk & Mulley, 2017) and autonomous buses (Piao et al., 2016). Transport operators like Transdev and Keolis (as well as bus manufactures) are looking into driverless minibuses and have already introduced pilot schemes (in closed environments with a supervisor on board at all times) around the world (e.g., Perth, Singapore, Paris). A prominent issue is how users' knowledge of whether their service is driverless influences their preferences and support for automation. Coupled with the need to garner community support are the legislative and regulatory reforms required, including updating legal and liability models designed for another era (Glancy, 2015; Sun, Olaru, Smith, Greaves, & Collins, 2016).

3.2 Ownership models and implications

Autonomous vehicle technologies have been said to improve travel flow and throughput (Talebpour & Mahmassani, 2016), premised on reducing headway (distance between vehicles), narrowing lane widths, optimising lane merges and development of autonomous intersection management to facilitate the most efficient junction movements without the use of traffic signals (VanMiddlesworth, Dresner, & Stone, 2008). On some estimates, full automation can, in an ideal scenario[7], increase throughput by nearly 500 percent over the status quo (Fernandes & Nunes, 2012)[8]. What remains unclear, however, is its net impact on congestion as the urban form morphs to reflect this increased accessibility. Induced demand will also arise from (i) existing drivers as the time freed en route may encourage them to travel further (related to location choice over the medium and long term) and more often; (ii) from non-drivers (Harper, Hendrickson, Mangones, & Samaras, 2016), either by choice or circumstance despite it being positive for social justice and transport equality; as well as (iii) from the influx of zero-occupancy vehicles deadheading to avoid parking or to reposition for their next trip. On-street parking (accounting for 30 percent of road space by some estimates) may also be eliminated or greatly reduced to increase road capacity, further inducing traffic. This also applies to off street parking (according to Ben-Joseph (2013), accounting for more than one third of land use in some American cities), which if eliminated will result in higher urban densities and more demand for travel.

Perhaps the greatest unknown, however, is the likely future ownership model for autonomous vehicles, which will determine the number of vehicles in the system and the proportion of time vehicles are spent out on the road. Some have suggested that due to their high cost, autonomous vehicles will be deployed to TNCs or mobility service providers first (Davidson & Spinoulas, 2016), who will likely desire greater returns through higher use (providing automated taxi services) as compared with individuals (the existing paradigm being private vehicles lying idle 95 percent of the time). Others propose an own and share model (Musk, 2016), where privately-owned Teslas will be available for autonomous ridesourcing when not in use (see additional discussion in Section 7.1). Finally, outright ownership models similar to the status quo are also in play premised on people's reluctance to share. A hybrid model featuring a mix of these owners is likely to emerge, depending on

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[7] Based on motorway travel at 120 km/h.

[8] See results of alternative modelling based on Lisbon, Portugal in Section 7.1.

user characteristics. For instance, Arbib and Seba (2017) suggests that by 2030, 40 percent of cars will still be privately owned, but account for just five percent of vehicle kilometres travelled, recognising the many car enthusiasts in the community as fleet managed vehicles (with an order of magnitude fewer vehicle count per capita) ply the system delivering transport for the masses.

3.3 Other technological developments

Closely coupled to vehicle automation are other technologically-led innovations which will transform the urban passenger transport sector. New vehicle propulsion technologies and the electrification of road transport will further revolutionise the industry. Electrification is unlikely to alter the geometric paradigm of ownership models and travel behaviour implications, although if they were linked to household power production (e.g., by supplying a top up function), there may be a need for greater vehicle ownership across the community. There are now even forays into the third dimension, with Uber’s Advanced Technologies Group investigating how vertical take-off and landing aircraft, supported by ‘vertiports’ can play a role in future urban transportation (Uber, 2016). The group envisages that under its ridesharing model, on demand aviation can become sufficiently affordable and attractive as a form of daily transportation for the masses.

Similar thinking has also taken hold at Airbus, where futurists and engineers have been developing three products—Project Vahana, a software platform for booking urban air mobility; Skyways, unmanned drones for freight transportation; and CityAirbus, a flying taxi prototype for passengers. These forays are all led by A^3, the company’s Silicon Valley research outpost aiming to define the future of flight (Airbus, 2016). Whilst there is significant interest in these propositions, and the merits of sacrificing low altitude airspace for freight and passenger transportation must be reexamined, the same questions regarding technological implications for vehicle kilometres travelled and the proportion of travel under a zero-occupancy setting will continue to arise. Regulations will be required surrounding new safety challenges as well as to minimise externalities on the urban realm (perhaps only permitting flight above existing roads below a certain altitude?).

4. Demographic change

Some of the sharing models described are contingent on demographic change and a shift in thinking across the community on shared mobility and vehicle ownership. Whilst obtaining a driver licence and owning a vehicle were once a ‘rite of passage’ for teenagers; this aspiration, despite great inertia, is quickly changing. Some say that baby boomers obtained freedom through their cars, whilst millennials seek freedom through mobile communication devices, and that the percentage of young drivers is inversely proportional to the availability of the internet. There is evidence of youth licensing decline across developed economies, though Delbosc and Currie (2013) suggests that this may be more the result of increasing educational participation and decreasing full-time employment rates, rather than attitudinal changes in cars no longer being a status symbol, nor ideology around climate change and sustainability. Indeed, Australia leads in youth licencing decline, though this has not translated to reducing the quantity of registered passenger vehicles per capita (Mulley, 2017). Other authors, however, have found that millennial changes in car ownership attitude and the use of virtual media can, for instance, account for some 35-50 percentage drop in driving in the United States (McDonald, 2015).

Millennials and young consumers are also the driving force behind the growth of the access or collaborative economy, willing to rent goods and services on demand rather than acquiring them permanently. Intermediate modes of transport imply a higher level of personal intimacy than mass transit—a psychological barrier for some users (Gardner & Abraham, 2007). Importantly, is the distinction between millennials' disposition to share on social media and their propensity to share personal space. A final demographic factor relates to an aging population, with increasing life expectancies leading to a greater proportion of dependents who can no longer drive (Shergold, Lyons, & Hubers, 2015). Whilst these demographic factors appear to point towards the right direction, positive network effects are far from guaranteed, particularly in conjunction with other factors in this emerging transport paradigm.

5. Digital technologies

The aforementioned drivers of collaborative consumption, next generation vehicles and demographic change are all predicated on the digitalisation of the economy—its significance hailed as the fourth industrial revolution. Any collaboration consumption model is contingent on a broker and an application interface which can bring demanders and suppliers together in real time. Autonomous and connected vehicles are digital technologies in themselves, aided by intelligent transport systems, the internet of things and big data analytics. Finally, demographic and attitudinal change accompany the emergence of digital technologies, though the direction of causality is less clear. The emerging transport paradigm constitutes a rare and unpredictable technological revolution, against a backdrop of incremental advances and social equilibrium—a standard pattern of evolution described in Dokko, Nigam, and Rosenkopf (2012). This technology-push force works in conjunction with market or demand-pull forces (Coombs & Richards, 1991), hence the recurring theme around user testing new propositions. These digital technologies offer the potential for more efficient vehicle use, optimising transport networks, better utilising infrastructure and delivering a more seamless customer experience (Kamargianni & Matyas, 2017). These outcomes, however, are not guaranteed—as technology does not drive change, but rather, technology only enables change (Mulley, 2017). Appropriate regulatory structures and other mechanisms must therefore be in place to guide these forces and secure the desired outcomes for society.

6. Implications for urban efficiency: The modal efficiency framework

The preceding literature review raises important questions on the impacts of this emerging transport paradigm on travel behaviour, vehicle ownership and urban efficiency. Specifically, the advent of collaborative consumption is leading a push towards smaller and more flexible (point-to-point) modes of transport. Questions remain surrounding the sustainability of various business models, and their impacts on the urban realm. How will public transport patronage (and thereby funding) and private car ownership be affected? What are the implications for these intermediate modes as autonomous vehicle technologies come online? What are the wholescale impacts of this emerging transport paradigm on road capacity, traffic congestion, land use and the urban form? To answer these questions, it is necessary to consider the plethora of new transport modes (including distinct ownership models) enabled by various digital disruptors and develop a framework with which to evaluate their suitability for a variety of urban environments.

Table 1 organises the collection of new mobility options (intermediate modes) introduced in Sections 2-3 according to relevant attributes as part of this emerging transport paradigm. Naturally, the full range of service possibilities cannot be considered within the constraints of this paper, but the focus will be on some of the major forces, their implications for urban efficiency, and a potential integrative transport solution which can help circumvent arising externalities and optimise this future transport landscape.

Table 1: Existing and emerging intermediate urban passenger transport modes defined by various attributes

Mode	Product	Ownership	Relevant Attribute	Example(s)[9]
Road (Manual)	Cycle Hire	Fleet	Station-Based	*Melbourne Bike Share*
			Roaming	*oBike*
Road (Motorised)	Ridesourcing		Point-to-Point	*Taxi*, *UberTaxi*, GrabTaxi
		Peer-to-Peer	Point-to-Point	*UberX*, GrabCar
			Point-to-Point (Luxury)	*UberBLACK*, *UberLUX*
	Driver-sourcing		Point-to-Point	Didi Chauffeur
	Ridesharing (Organised)		Destination-Based	Co-*Hop*
	Ridesharing (Casual)			UberCOMMUTE
			Social	GrabHitch
	Microtransit (Point-via-Point(s) to Point)		Commercial	*UberPOOL*, GrabShare, Lyft Line
		Fleet	First/Last Mile	Didi Minibus
			Fixed Route	UberHOP, Didi Bus, GrabShuttle, Lyft Shuttle
			Fixed Route (Luxury)	Leap, *SuitJet*
	Carsharing		Round-Trip	*GoGet*
			One-Way	Car2Go
			One-Way (Coupled)	ESPRIT[10]
		Peer-to-Peer	Round-Trip	Car *Next* Door
Road (Autonomous)	Automated Taxi		Point-to-Point	Autonomous Tesla[10]
		Fleet		nuTonomy
Air (Motorised)	Helicopter			UberCOPTER
Air (Autonomous)	Flying Taxi			Uber Elevate[10], CityAirbus[10]

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[9] Australian examples are used where possible and shown in italics.

[10] Under development—services not yet in commercial operation.

The efficacy of various transport modes can be considered with reference to their spatial and temporal efficiencies—their ability to reap economies of scale by delivering maximum transportation across space (carrying multiple people per unit area) and time (providing mobility rather than lying idle). To consider the implications of the emerging transport paradigm for urban efficiency, it is necessary to develop an ordinal measure for modal efficiency in terms of spatial and temporal efficiencies. In this spirit, the *modal efficiency framework* (Figure 1) situates public, private and intermediate modes in each quadrant within a space-time plane defined by axes representing spatial and temporal efficiencies. Spatial efficiency is defined as passengers per vehicle/train consist (or per unit road space) whilst temporal efficiency can be considered as the proportion of time a vehicle spends on the road (in revenue service for public transport). Axes scales are estimated and intended to be illustrative only.

Public transport (or specifically, mass transit), is both spatially efficient in bringing large numbers of people onto a single vehicle[11], as well as temporally efficient, by providing service around the clock[12]. Conventional taxis are temporally efficient but not spatially efficient, and constitute the sole intermediate mode which has prospered without the aid of digital technologies. Private transport like the car is neither spatial nor temporally efficient, with an average occupancy of 1.2 people per vehicle (for journey-to-work) and spending 95 percent of the day idle (parked either at home or at a destination). Intermediate modes which have recently emerged or are currently in development (with a selection of the most prominent propositions from Table 1 featured) are less spatially efficient, but have the potential to be temporally efficient through shared models of ownership—for example, by a TNC or mobility provider. As expected, there is a direct correspondence between the spatial efficiency axis and vehicle occupancy (sole, shared or mass) and between the temporal efficiency axis and the ownership model (private, peer-to-peer or fleet managed) of vehicles or the service.

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[11] A caveat is an empty bus scenario.

[12] The extent of this across the fleet can be measured by metrics such as the operational peak-to-base ratio.

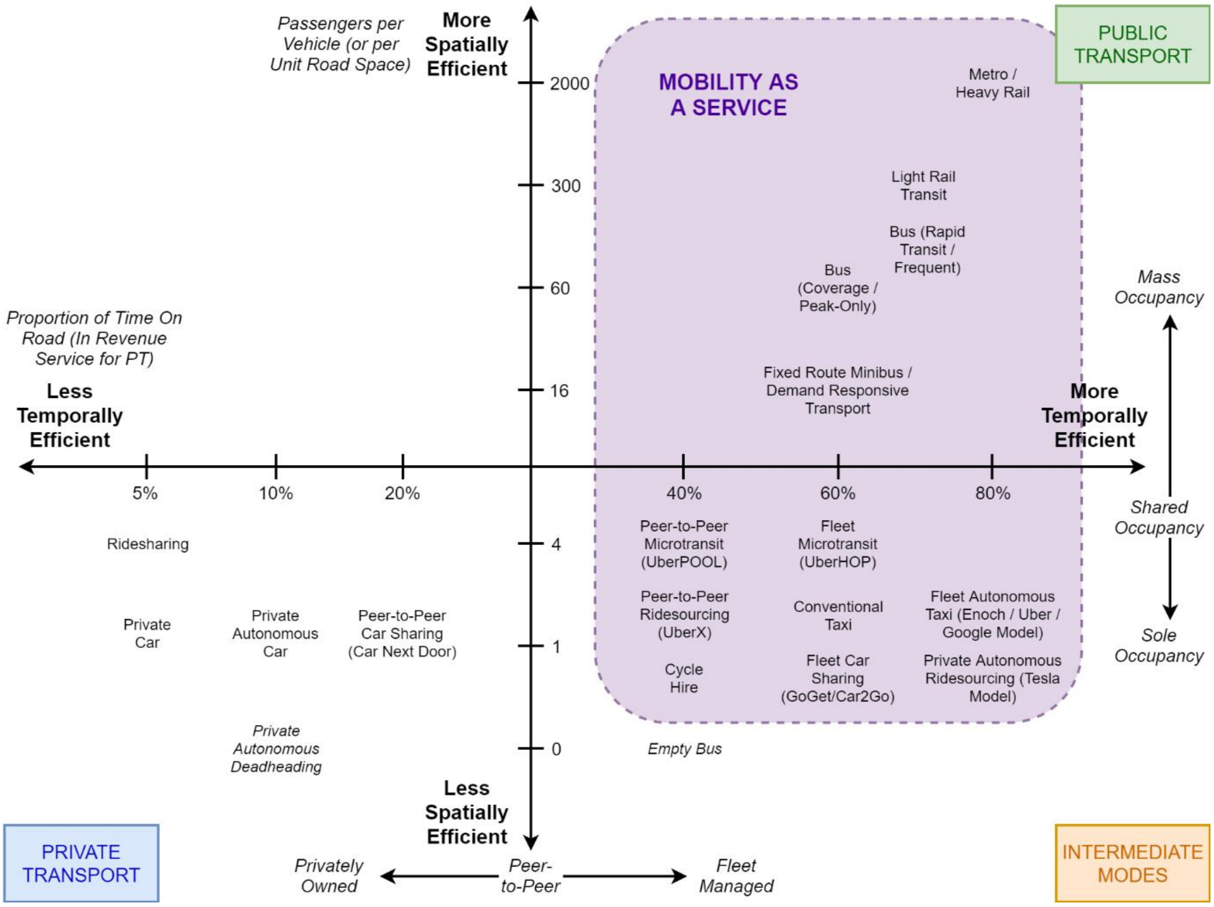

Figure 1: The *modal efficiency framework* situating public, private and intermediate modes with respect to their spatial and temporal efficiencies—mobility as a service (MaaS), to be introduced in Section 9, offers an integrative solution bringing together temporally efficient modes across a range of spatial efficiencies

7. Future scenarios for modal development

Whilst Sections 2-3 and Table 1 introduced a plethora of emerging intermediate modes enabled by digital technologies, this section looks to how these modes may further transform or converge. Their development is evaluated with greater specificity and with reference to the modal efficiency framework. Three potentially problematic scenarios have been proposed by the authors—(1) modal convergence towards an automated taxi service, (2) microtransit displacing and replacing fixed route public transport, and (3) microtransit evolving into fixed route public transport. One nuance is how models (2) and (3) may differ between first/last mile and trunk public transport which will feature in the subsequent discussion of Section 8.

7.1 Modal convergence to automated taxi service

Automated taxis (also known as driverless taxis, robo-taxis or taxibots) have garnered great interest in both academic and popular literature, and are often regarded as a panacea for urban passenger transportation by being able to deliver point-to-point services at low cost. The exact cost and service differential relative to public transport and private cars will likely determine its take-up and market share. Some authors, however, see an automated taxi service becoming the sole mode of transport available in the long term. Enoch (2015), as a prominent example, envisages a model where buses (due to the desire for point-to-point service), cars (due to externalities) and taxis (due to a desire for lower cost) converge to become a universal automated taxi system. Stated preference work like Krueger, Rashidi, and Rose (2016) attempt to predict the possibilities and impacts on travel behaviour. Whilst Enoch (2015) recognises the issue with urban sprawl and increased vehicle kilometres travelled, he ignores road space as a scarce commodity in dense urban environments. Point-to-point transportation is by definition low volume and associated with sole or low occupancy vehicles which take up more road space per passenger transported (being less spatially efficient)[13]. Further, autonomous vehicle technologies will bring the problems of induced demand as introduced in Section 3.2.

The Enoch (2015) modal convergence hypothesis is premised on a taxi model (operated by a mobility provider) which is far more temporally efficient than an ownership model where vehicles owned by individuals continue to dominate the mobility paradigm. More intriguing is an own and share model, as suggested by Musk (2016), where autonomous vehicles (Teslas) are owned privately but hired out when not in use for ridesourcing. Temporal efficiency in this case will depend on the proportion of the population owning vehicles, which by extension determines the demand for ridesourcing and the relative amount of time these vehicles will spend deadheading. Peaking issues also come to mind where there will either be an abundance of empty vehicles or a lack of vehicles providing ridesourcing services out on the road[14].

The system design, operation and congestion impacts of an automated taxi service regime has been the subject of some very advanced modelling. A recent study (Martinez & Crist, 2015) conducted by the International Transport Forum in Lisbon, Portugal found that under a sole passenger driverless taxis scenario with 92 percent mode share (the other 8 percent on active modes with 0 percent using public transport), only a quarter of the existing car fleet will be required—though these will be used far more efficiently across time, doubling current vehicle kilometres travelled. This model also suggested that there would be only a minor increase in average travel times, based on the proposition that less than 40 percent of Lisbon’s roads were used in peak periods. Further investigation revealed that distributors will see traffic increase by 76 percent and local roads by 115 percent, disregarding the road hierarchy and turning over communities where pedestrians ought to have priority to motorised modes, bringing associated noise, air and urban amenity externalities.

7.2 Microtransit displaces and replaces fixed route public transport

The growth of microtransit can be attributed to a broader desire to provide more personalised service than conventional public transport, which features an access/egress component to and from the public transport stop or station, set schedules, and often less direct routing.

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[13] Even accounting for the likely headway reduction enabled by full autonomous vehicle deployment.

[14] Similar to the developing world paratransit experience where there is either an oversubscription (too many vehicles) or overcapacity (not enough vehicles)—due to vehicle drivers operating as individual agents (not coordinated as part of a system) and the lower capacity of paratransit vehicles (leading to less latent capacity to meet peak demand).

Intermediate modes first emerged many decades ago as “unconventional modes” (Nutley, 1988), filling both a welfare obligation (as community transport to the disabled and elderly), and to fill a gap in service to compete with the private car. Many such flexible transport services (including dial-a-ride) have been driven by the impetus to reduce the cost of public transport provision, especially during evening and weekend periods when many services run empty[15]. The use of smaller vehicles is generally not a motivation because of the extra fleet which would be required (Walker, 2012).

Dedicated systems with their own right of way have even been proposed or implemented—like the Cabinentaxi (Hesse, 1972), and more recently, the Masdar Personal Rapid Transit—without great success, despite initially seen as the future of urban passenger transportation (much like automated taxis are today). The growth of microtransit also has links with developing world paratransit[16], ubiquitous across Africa, south Asia and Latin America. These services have long been regulated out of developed countries, with Hong Kong being a prominent exception where public light buses have been integrated within the public transport regulatory framework (Lee, 1989). There is a strong parallel between TNCs providing ridesourcing and microtransit with (for instance) South African minibus taxis, which have proven to be a sustainable business model. Both utilise independent contractors driven by the profit motive, though the microtransit model is enabled by digital technologies which better connect demanders and suppliers.

In the same way that minibus taxi associations have been able to force out conventional fixed route public transport (buses) in South Africa, albeit under a lapse in regulation, enforcement, and with incredible violence; TNCs may pick the cream and begin to undercut heavily profitable bus routes. One major issue is the unfair playing field as TNCs do not own their own fleet, have no social obligation to provide service, and do not treat their driver/partners as employees (with related on-costs like worker’s compensation). As the destructive cycle begins, governments will have less impetus to subsidise increasingly costly public transport—further accelerating its decline. Microtransit working in competition with mass transit provides point-to-point transportation, abolishing connections to “take people all the way to their destination” (Musk, 2016). People will stop feeding into buses and buses stop feeding into railways (towards more spatially efficient modes), but rather, use smaller vehicles to travel directly to their destination. The result of smaller vehicles is significantly greater vehicle kilometres travelled (with implications on emissions and congestion) and less impetus for developing transit-conducive urban design (and hence reaping the agglomeration economies of cities). There will also be the issue of replacing the current access/egress component in terms of the walk to public transport stops or stations with motorised transport, with impacts on health and social inclusion. These hypothesised impacts depend on commuters’ willingness-to-pay for a more personalised service and the fare differential between microtransit and conventional public transport. Stated choice experiments like Frei et al. (2017) constitute one way for establishing this future.

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[15] Canberra’s Flexibus (since discontinued due to difficulty coordinating inbound pick-ups) and their recent BusPlus proposal (cancelled before implementation) are such examples attempting to reduce cost.

[16] Paratransit in the developing world refers to flexible transport services, usually with small and medium-sized buses not following fixed routes and schedules—different to the United States where use of the term is associated with transport for the disabled, as required by law.

7.3 Microtransit evolves into fixed route public transport

Whilst there are proponents of flexible bus services (in effect, microtransit), their efficiency and scalability remains questionable and the wholescale removal of fixed stops, routes and timetables ignores the intrinsic value in accessibility. The future of microtransit can again be related to the history of minibus taxi development in South Africa (as an example). What began as sedans offering shared taxi services in townships slowly grew in size to become combis and minibuses, developing increasingly fixed route structures during this process (McCaul, 1990). In major town centres, there are even designated stops where customers are encouraged to board and alight. In many ways, these paratransit services operate as fixed route buses with ‘fill-and-go’ and ‘crawling’ behaviour as opposed to set schedules (Behrens, McCormick, & Mfinanga, 2015).

This development confirms the operational merits of fixed route public transport, as reflected by increasing instances of microtransit taking on a more rigid form. Uber Smart Routes, for instance, offers a discount for customers walking to a major arterial to access their UberPOOL. Indeed, there are benefits to meeting points in ridesharing systems (Stiglic, Agatz, Savelsbergh, & Gradisar, 2015; Teubner & Flath, 2015), due to the economies of scale achieved at each stop. New services like UberHOP even use bus-sized vehicles and charge fixed prices much like conventional buses. CityMapper, an application developer, recently launched Smartbus, using midibuses on a crowd-sourced fixed route in Central London. These trends suggest a possible alternate future for urban efficiency, though the issue of a level playing field once again emerges as the demise of government operated/subsidised services brings externalities for the labour market and issues for social inclusion.

8. Spatial and temporal integration opportunities

Ultimately, each mode constitutes a trade-off between various attributes, including service quality and quantity (e.g., comfort, an ability to personalise travel space, speed, reliability, directness), with spatial and temporal efficiency. The modal efficiency framework (Figure 1) constitutes one attempt at explaining why some of these emerging transport modes and scenarios for their subsequent development may be geometrically incompatible with dense urban environments. Clearly, there is time and place for each mobility proposition, and an integrated system is required to deploy the most appropriate mode for each urban environment, consistent with the policy objectives of government. Modal integration will ensure that the transport system is network efficient, not just efficient for each mode or operator. For instance, ridesourcing or microtransit, whether manually-operated or autonomous (Ohnemus & Perl, 2016) can provide first and last mile connections in suburban locales to mass transit corridors which service the densest urban environments (Shaheen & Chan, 2016).

This is especially important given the trend towards the consolidation of bus routes for higher frequency, increased stop distances and reduced coverage services (Nielsen et al., 2005; Walker, 2008). The success of Metrobus in Sydney (Ho & Mulley, 2014), Smartbus in Melbourne, and growth of other branded bus services (Devney, 2011) are cases in point.

Such trunk and feeder systems, with a divergence in service (mass transit on thriving arterials and dense locales; microtransit or ridesourcing in marginal environments) meets the spatial constraints of the urban realm. Indeed, the intermediate modes outlined in the modal efficiency framework ought only be deployed where there is a cost advantage and geographic impetus for such services.

Whilst trunk and feeder systems constitute a spatial integration of public and intermediate modes, there also exists the opportunity to integrate across the temporal dimension of transport service provision. All modes of transport seek to meet peak demand (Walker, 2012), when roads are most congested and public transport most crowded. For public transport agencies, peak demand defines vehicle requirements, vehicle capacities as well as staffing levels (Vuchic, 2005). Peak transport costs are highest as these additional vehicles are procured and personnel employed to service peak periods exclusively (De Borger & Kerstens, 2007; Walker, 2012), sitting idle and unproductive at other times of the day. There exists a significant negative correlation (Nolan, 1996) between the peak-to-base ratio[17] and technical efficiency in the use of resources, through impacts on service scheduling (García Sánchez, 2009; Iseki, 2010). The temporal efficiency of public transport as defined in the modal efficiency framework is hence a function of its operational peak-to-base ratio, with temporal integration between public and intermediate modes offering the potential to further enhance temporal efficiency.

There is again a link with the South African experience, as minibus taxis operate illegally and compete on road with new bus rapid transit systems[18], despite having been compensated by government to exit the market. These illegal entrants operate essentially as a top up service on the bus rapid transit base load[19], representing a form of temporal integration and saving 30-40 percent in bus rapid transit peak vehicle requirements (personal communication: Transport and Urban Development Authority, City of Cape Town, 14 February 2017). Similarly, digitally-enabled intermediate modes can provide a top up service to the conventional public transport base load in developed economies (Figure 2), saving peak service costs. One weakness with this model is that it outsources the most expensive (peak) service to independent contractors, bringing potential issues in the social dimension (Rogers, 2015). Work has also been done plotting the distance decay function for temporal variation in transit patronage—namely, how the patronage peak-to-base ratio varies with increasing journey distances (Wong, 2015). This suggests that there are particular geographic contexts where this model of temporal integration is most applicable and useful for maximising urban efficiency.

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[17] Defined as the quotient of peak vehicle requirements and vehicle requirements in the inter-peak (usually calculated at midday).

[18] Rea Vaya in Johannesburg and MyCiTi in Cape Town as examples.

[19] This compares with the traditional model where minibus taxis service the base load and conventional buses provide the top up (forced out due to taxi violence and intimidation), completing perhaps two trips per day and representing a very poor utilisation of resources.

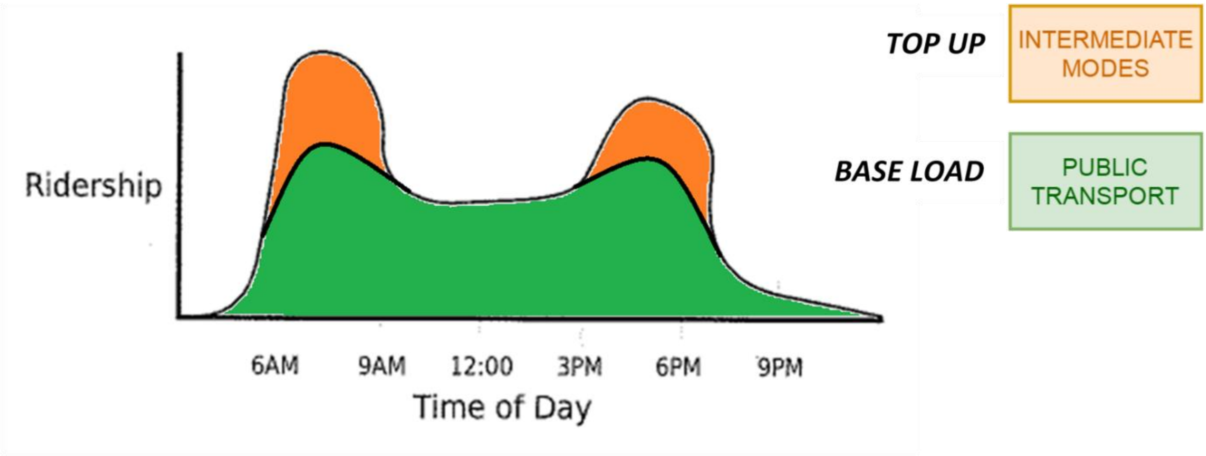

Figure 2: Potential model for temporal integration between public transport and intermediate modes, based on the South African bus rapid transit / minibus taxi integration experience (base diagram from Walker (2012: 77))

Spatial and temporal integration objectives necessitate an integrated transport regime which brings together public transport and intermediate modes. There already exists an abundance of literature on transport integration (Chowdhury & Ceder, 2016; Grotenhuis, Wiegmans, & Rietveld, 2007; Mulley & Moutou, 2015; Preston, 2010), mainly surrounding customer preferences, government policy and regulatory structures. Theoretical antecedents for integration are based around search economies, enhanced customer satisfaction and an improved total image for business (Guiltinan, 1987). However, existing integration appears to be centred around different public transport modes (bus, rail, etc.), and are only just beginning to incorporate emerging intermediate modes of transportation. Exceptions include cycle hire schemes which are prominent in Europe and park and ride facilities which attempt to bring together public and private modes of travel.

New partnerships are now being developed between city authorities, public transport operators and TNCs in the United States (see different tiers of partnership proposed in Campbell (2016)) and also Australia (Canberra’s Night Rider being a national first), in terms of providing first/last mile connections to and from fixed route public transport. Various transport smartcards (e.g., Oyster in London) are seeing their functionality extended to encompass access to carsharing services (Kamargianni, Li, Matyas, & Schäfer, 2016). Integrated mobility services (Hinkeldein, Schoenduwe, Graff, & Hoffmann, 2015) can circumvent some of the potential externalities associated with the emerging transport paradigm—such as a proliferation of zero occupancy vehicles autonomously roaming the network, or a destructive cycle where mass transit is increasingly replaced by less spatially efficient point-to-point transportation.

9. A case for mobility as a service (MaaS)

Mobility as a service (MaaS) offers an integrative solution which brings together temporally efficient modes across a range of spatial efficiencies (Figure 1), thus incorporating both public and intermediate modes of transportation (private transport being provided through sharing). Also known as transport as a service (TaaS)[20], combined mobility, integrated mobility or mobility services, MaaS can be defined as a personalised, one-stop travel management platform digitally unifying trip creation, purchase and delivery across all modes. MaaS is growing increasingly mainstream in both theory and practice, with a bourgeoning literature base (Table 2) and innovative trials underway around the world (e.g., Helsinki, Birmingham).

A major component in the design and implementation of MaaS are the *three B*s bundles, budgets and brokers (Hensher, 2017). A key innovation in MaaS is the ability for customers to purchase '**bundles'** of mobility which grant them a defined volume of access to each mode for a specified level of service. This opens up an opportunity for the mobility provider of such integrated system to (in real time) price people[21] away or towards certain routes/modes per time of day, and even completely degenerate a trip. **Budgets** relate to end user preferences and service provision possibilities. A key consideration concerning the take up of MaaS or shared mobility accessed as a *service* is the willingness of people to move from low marginal cost transport—i.e., vehicle ownership, where the cost of purchase (and sometimes even maintenance and government charges) are perceived as 'sunk'—to high marginal cost transport, where one pays the true (private) cost per trip or period of time. Stated choice investigations in Matyas and Kamargianni (2017) and Ho, Hensher, Mulley, and Wong (2017) offer welcome insights into the community's willingness-to-pay for mobility packages, helping forecast demand, estimate mode shares and inform the design of MaaS for either commercial viability or societal optimality. Finally, **brokers** refer to the business models around which MaaS will be delivered, including the potential for new entrants (from non-mobility suppliers like technology startups, banks and property developers) and implications on existing public transport contracts (Hensher, 2017).

Table 2: Academic literature (journal articles and research theses) to date specific to mobility as a service

Publication	Principal Technical Topic	Nature of Analysis
Mulley (2017)	Implementation and scalability of mobility as a service	Editorial
Matyas and Kamargianni (2017)	Stated choice investigation on demand for mobility as a service packages	Empirical (London, United Kingdom)
Kamargianni and Matyas (2017)	Potential business models for delivering mobility as a service	Think piece
Hensher (2017)	Future of public transport contracts under mobility as a service	Think piece
Sochor, Karlsson, and Strömberg (2016)	Travel behaviour impacts of mobility as a service, based on ex-ante and ex-post questionaries and interviews with users	Based on data from Sochor, Strömberg, and Karlsson (2015)
Mukhtar-Landgren et al. (2016)	Institutional requirements for implementing mobility as a service	Think piece
Kamargianni et al. (2016)	Integration opportunities and evaluation of existing mobility as a service schemes	Literature review

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[20] In the United States.

[21] Akin to off-peak fare discounts on public transport (but in real time, across all *modes* of travel and to more temporal specificity)—Uber's Surge Pricing is perhaps a more salient (yet controversial) example.

Giesecke, Surakka, and Hakonen (2016)	Conceptual issues in mobility as a service implementation for users, infrastructure and sustainability	Think piece
Brendel and Mandrella (2016)	Information system requirements for mobility as a service	Literature review
Sochor et al. (2015)	Stakeholder expectations on mobility as a service, based questionnaires and interviews with users, the mobility provider and government	Empirical (Gothenburg, Sweden)
Rantasila (2015)	Potential impacts of mobility as a service on land use	Interviews (Helsinki, Finland)
Hu, Giang, Shen, Leung, and Li (2015)	Evaluation of mobility cloud service for smart transportation	Product evaluation
Heikkilä (2014)	Government interest in mobility as a service and industry transition opportunities	Think piece

A major omission based on a comprehensive review of the MaaS literature (Table 2) concerns the theoretical rationale for implementing such an integrated mobility product. Whilst the user benefits in terms of true competition with vehicle ownership (transforming mobility based on asset ownership to one where it is consumed as a *service*) and a seamless customer experience, as well as the benefits for service providers by improving the capacity utilisation of their vehicles and opening up new opportunities for forward-thinking businesses are well developed, there remains limited recognition in terms of the societal imperative for MaaS. An emerging transport paradigm driven by the range of digital disruptors developed in this paper will bring a variety of externalities which MaaS can help circumvent. The potential here, however, depends on the exact service delivery model or broker-government interface for MaaS.

At present, MaaS is being implemented in a (somewhat) policy vacuum, driven by the market with limited government interference. Companies like MaaS Global and bodies such as MaaS Alliance (both of which constitute cross-sector industry collaborations) are driven by a commercial imperative which may or may not align with government goals for transport and land use. As an example, intermediate modes are usually more lucrative operating with higher margins (profits) than heavily subsidised public transport operators whose businesses are generally very marginal. As a result, there may be greater substitution in these MaaS schemes from public transport towards intermediate modes (consistent with all scenarios developed in Section 7). Under this economically deregulated model, there may be the opportunity to move from self-regulation towards government acting as an independent regulator similar to the Office of Rail and Road (ORR) and the Water Services Regulation Authority (Ofwat) in the United Kingdom, to define conditions around safety and fair competition in the MaaS marketplace.

The alternative is a government-contracted model which adds an institutional overlay to impose conditions such that service delivery is consistent with societal objectives. This offers the best opportunity for achieving a societal equilibrium based on network efficiency and the equating of marginal social costs with benefits. The government can directly procure a mobility broker through a competitive tender, with the opportunity to negotiate contract renewal (under actionable benchmarking) at subsequent rounds once the market has matured—the present best practice in public transport service contracts (Wong & Hensher, 2017). The government can set accessibility standards, including key performance indicators such as delivering X percentage of people services within Y minutes, for a given period using any mode of their choosing; thus reflecting the increasing shift from output-based towards outcome-based contracts. To maintain the full range of service offerings across spatially efficient modes and for transport equity considerations, there exists the prospect of government support and the opportunity for government to guide the conditions of operation.

Perhaps the greatest opportunity under a MaaS model is the ability for government to regulate for network efficiency by incorporating road pricing as an input into package price. Whilst road pricing has been on the agenda since the 1960s, there has only been limited implementation around the world. Both cordon-type charges (e.g., in London, Singapore) and road tolls (e.g., public/private motorways in Sydney) constitute flawed systems which distort the market rather than maximising for network efficiency. MaaS, in bringing together *all* modes of travel, allows an easily implementable system of great sophistication which can price according to time of day (to the minute), geography (by location and road type) and modal (both spatial and temporal) efficiency. Both time of day and geography (themselves spatial and temporal elements) are well regarded in their ability to correct for market failures and to internalise negative externalities. The spatial mode price can reflect a level of cross-subsidisation between intermediate modes and public transport (through mandated pricing ratios, for instance), such that the additional externalities associated with point-to-point transportation can be priced, thus helping shift users onto more spatially efficient modes. The temporal mode price favours fleet managed systems (e.g., carsharing) over peer-to-peer and private ownership, with links to sustainability as well as freeing up road space occupied by parked vehicles[22].

MaaS ought to have as its stated goals not only to deliver a seamless customer experience across all modes of travel, but also to align with the urban efficiency objectives of cities as dense urban environments. In this paper, we have presented an emerging transport paradigm driven by a range of digital disruptors. There is widespread enthusiasm over these technologies, but a lack of clarity on their travel behaviour impacts, including a poor recognition that it may lead to a more virulent form of the existing transport paradigm. The lesson here is that whilst “change is certain, progress is not” (E. H. Carr). The challenge, therefore, is to garner the enabling role of technology and to disrupt the transport system to our advantage—for societal, rather than commercially-driven objectives. Government-led MaaS, based on road pricing as an input into package price can help deploy the most appropriate mode for each urban environment (informed by the modal efficiency framework), thereby maximising urban efficiency to deliver a societal equilibrium.

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[22] Parking charges may be incorporated as part of MaaS and thus no longer required as a standalone system.

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