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Smart Cities — Infrastructure and Information

Editors

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Editorial

Three Tales about Limits to Smart Cities Solutions

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Abstract
This editorial is the introduction to a special issue on smart cities. The concept of a smart city is not well-defined, yet expectations among urban planners and decision-makers are high. This special issue contains three papers that discuss three different manifestations of smart cities and the success—or lack of it—of the solutions discussed. The papers highlight some limitations of the concept of smart cities, but at the same time also pinpoint some potentially beneficial solutions.

Keywords
Mobility as a Service; smart cities; smart mobility; urban interventions

Issue
This editorial is part of the issue “Smart Cities—Infrastructure and Information”, edited by Soora Rasouli, Harry Timmermans, and Dujuan Yang (Eindhoven University of Technology, The Netherlands).

Not a week passes, but we receive an invitation for some conference on “smart cities”. Remarkably, conference locations are scattered across the world: from Korea, via the Gulf States to Brazil and many countries in between, witnessing the worldwide popularity of the smart cities concept. Cities want to be smart (who doesn’t?). It seems local governments believe it is not smart to miss out on this trend of epidemic proportions. Smart city has become a buzz-word, which has started to lose much of its specific meaning. Interviews with decision makers and politicians reveal the term has become an umbrella concept with a plethora of annotations, which is interchangeably used for sustainable cities, resilient cities, low-carbon cities, eco-cities, digital cities, ubiquitous cities and several other terms.

The European Initiative on Smart Cities seems founded on a narrower definition. It is derived from the strategic objective “to demonstrate the feasibility of rapidly progressing towards its energy and climate objectives at a local level while proving to citizens that their quality of life and local economies can be improved through investments in energy efficiency and reduction of carbon emissions… . This will require systemic approaches and organizational innovation, encompassing energy efficiency, low carbon technologies and the smart management of supply and demand. In particular, measures on buildings, local energy networks and transport would be the main components of the Initiative”.

Essential for smart cities is the application of advanced information and communication technology to supplement conventional planning and marketing tools. Traditionally, urban planning and design concern the development of physical environments that cater the needs and well-being of their citizens, support the economic activities of the city, while minimizing environmental impact. Over the years and across countries that differ in their urban planning tradition, the role of urban planning has varied considerably. In some cases, urban planning can take on a central orchestrating role; in other cases, it stimulates, supports or defines the boundaries of a multi-actor public-private partnership development process. While generally urban plans aim at improving the quality of life of citizens (and achieve additional economic and environmental objectives), there are limits to physical interventions in realizing these goals and objectives. Even in the ideal case that urban planners and designers perfectly know the needs and preferences of the citizens and physical environments can be created to perfectly meet these needs and preferences, the optimality can only be instantaneous as over time there will be a growing discrepancy between people's preferences and the properties and performance of the built environment. The fundamental problem here is that needs and preferences, both quantitatively and qualitatively, tend to change faster than what an inert physical environment can accommodate. The temporal scales of change differ too much, creating inefficiencies in the urban system.

New strategies for urban interventions that are enabled by emerging information and communication technologies thus allow bridging or narrowing this gap and guarantee a more effective and efficient use of urban spaces and urban networks, which will not only enhance people's quality of life but also better meet the environmental objective of reduced energy consumption. Advances in big data analysis, sensor, GPS and other technologies, and the creation of an Internet of Things provide the building blocks of a data-driven approach to urban planning and design. The omnipresence of ICT stimulates the development of solutions that people and business can use to improve the functioning of cities. Recommendation systems allow people to better find their places of interest and organize their daily activities. Parking systems guide drivers to find a vacant parking lot in congested urban areas, making more efficient use of limited space. Location based services signal when people are in a particular area, allowing businesses to offer personalized services. Digital technology can improve the use of the grid and reduce energy consumption. These are just a few examples of solutions and interventions that smart cities may embrace.

The hype about smart cities has the danger that expectations may be too high and that investments may be ill-founded. One of the roles of academic research in this context may be to monitor developments and progress, document failures, reflect on emerging trends and discuss findings both with academics and practitioners. The present special issue represents a small contribution to that endeavor.

In a fascinating paper on Songdo, Korea, Mullins (2017) convincingly discusses how city government has been struggling with the labeling of the strategic objectives underlying the plans for the city. The paper also supports our view that demand may change fast. Particularly, they discuss the impact of a cooling down of the world economy and how the city has been struggling to compete internationally for businesses and people, while maintaining its planning goals. The author argues that Songdo had difficulty to adjust to the changing world economy because planning followed a closed-system approach.

Smart cities are closely linked to smart mobility solutions. In part, this can be explained by the fact that transportation is responsible for a large share of energy consumption. In addition, transportation is amenable to smart solutions in the sense the big data that increasingly become available can be used to develop and offer dedicated, personalized solutions. The new ICT support the development of a platform economy. Platform businesses can be found in a growing number of industries. Mobility as a Service is the latest development in providing smart mobility solutions. In avoiding that people need to buy their own car, MaaS is expected to reduce traffic and its negative externalities. Jittrapirom, Caiati, Feneri, Ebrahimigharehbaghi, Alonso-González and Narayan (2017) provide an interesting overview of recent MaaS initiatives and pilot projects. Their paper shows that some initiatives were short-lived. On the other hand, the increasing number of projects and the spatial diffusion of Maas suggest that planners and decision makers still have high expectations. As academic research on the topic is scarce, there is a clear need for research that assesses the potential of MaaS and related developments.

Jalali, Koohi-Fayegh, El-Khatib, Hoornweg and Li (2017) present a perfect example of such studies, focusing on ridesharing in Changsha, China. The authors explore the potential of ridesharing among passenger vehicles to reduce vehicle pollutants and GHG emissions. Using big data (historical GPS data of approximately 8,900 privately-owned vehicles), a newly developed algorithm is used to calculate reductions in pollutants and GHG emissions for different scenarios of ridesharing. Results support the potential of ridesharing in improving air quality, although the impact depends on people's propensity to adapt and change their daily mobility routines.

Although we should be modest about a special issue pushing forward the research frontier, we view these articles as exemplars of the kind of research that urban planning can produce in realistically portraying the potential of smart cities in shaping future cities that improve people's quality of life and well-being in their multi-faceted meaning. Urban planning practice can only improve by learning about successes and failures and understanding how people, firms and institutions react and adapt to urban interventions as ultimately the performance of urban systems is nothing but the accumulated outcome of their decisions.

Conflict of Interests

The authors declare no conflict of interests.

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Article

The Ubiquitous-Eco-City of Songdo: An Urban Systems Perspective on South Korea's Green City Approach

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Abstract
Since the 1980s, within the broader context of studies on smart cities, there has been a growing body of academic research on networked cities and "computable cities" by authors including Manuel Castells (Castells, 1989; Castells & Cardoso, 2005), William Mitchell (1995), Michael Batty (2005, 2013), and Rob Kitchin (2011). Over the last decade, governments in Asia have displayed an appetite and commitment to construct large scale city developments from scratch—one of the most infamous being the smart entrepreneurial city of Songdo, South Korea. Using Songdo as a case study, this paper will examine, from an urban systems perspective, some of the challenges of using a green-city model led by networked technology. More specifically, this study intends to add to the growing body of smart city literature by using an external global event—the global financial crisis in 2008—to reveal what is missing from the smart city narrative in Songdo. The paper will use the definition of an urban system and internal subsystems by Bertuglia et al. (1987) and Bertuglia, Clarke and Wilson (1994) to reveal the sensitivity and resilience of a predetermined smart city narrative. For instance, what happens if the vision moves from the originally intended international-orientated population towards remarketing the city to attract a domestic middle-class population. The lens of the financial crisis in 2008 revealed that the inherent inflexibility of a closed-system approach in Songdo was not sufficiently resilient to external shocks. The shift towards a domestic middle-class population revealed the inequality in accessing the city services in a system designed with formalized and rigid inputs and outputs. By focusing predominantly on technology, the social dimensions of the city were not part of Songdo's smart city vocabulary. Therefore, in adopting a technologically deterministic approach (Mullins & Shwayri, 2016) to achieving efficiency and combating environmental issues, Songdo's green city model was found insufficient in its ability to cope with the complexity and dissonance that occurs in relation to "glocal" challenges facing cities today.

Keywords
eco-cities; Free Economic Zones; green city; smart city; Songdo; South Korea; sustainability; ubiquitous; urban systems

Issue
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1. Introduction

Over the last decade, governments in Asia have displayed an appetite and commitment to construct large scale city developments from scratch—one of the most famous being the smart entrepreneurial city of Songdo, South Korea. As noted by Mullins and Shwayri, "these twenty-first-century cities have been heralded as archetypal urban developments, owing to their focus on energy efficiency and low carbon emissions" (Mullins & Shwayri, 2016, p. 47). The global concern of climate change has re-conceptualized these new cities to address environmental concerns—such as carbon emissions to become "green" or "eco". As Federico Caprotti notes (2014, p. 8), the building of eco-cities is now at the "forefront of national and global agendas".

These newly-planned green cities all share the common approach to constructing urban systems based on low-carbon infrastructure (water recycling and automated collection systems), reducing and managing energy consumption (LEED certified buildings, photovoltaic power and thermal cooling), as well as securing land (30%) for green spaces to absorb carbon emissions. In this approach, it is the eminence of "harnessing technologies, including ICT" which has led to these green cities being classified under the more globally used umbrella term "smart" (Albino, Berardi, & Dangelico, 2015, p. 4). The use of the term "smart" in relation to cities has become particularly problematic due to its many "conceptual variants" and inconsistencies, as demonstrated by scholars Albino et al. (2015), and O'Grady and O'Hare (2012). However, in the Korean context, the terminology privileged by both private and public sectors has been "ubiquitous", and, as such, the "U" prefix has been readily adopted (U-Cities, U-Eco-City). The Ministry of Information and Communication in Korea define "Ubiquitous technologies" as "technology that allows everything around us to be networked for communicating with each other anytime and anywhere" (Ministry of Information and Communication, 2004, p. 4).

In Korea, as highlighted by Mullins and Shwayri (2016), the eco- or green-city approach to urban development has "become synonymous with the ubiquitous city concept and has been well-documented in recent scholarly discourse" (Mullins & Shwayri, 2016, p. 49). For instance, examining the Korean ubiquitous eco-city (Kim, Kim, Moon, & Bae, 2009), test-bed urbanism (Halpern, LeCavalier, Calvillo, & Pietsch, 2013), and the politics of developing the eco-city model in the case of Songdo (Shwayri, 2013). In the broader context of studies on smart cities, since the 1980s, there has also been a growing body of academic research on networked cities and "computable cities" by authors including Manuel Castells (1989), Michael Batty (1995), William Mitchell (1995), and Rob Kitchin (2011).

Using Songdo as a case study, this research will examine, from an urban systems perspective, some of the challenges of using a green-city model led by networked technology. A mixture of primary and secondary sources based on the authors first-hand experience of the city and geographical and cultural context were utilized to interrogate the urban system and internal subsystems in relation to Songdo. More specifically, this paper aims to add to the growing body of smart city literature by using an external global event—the global financial crisis in 2008—to reveal what is missing from the smart city narrative in Songdo. Using the definition of an urban system and internal subsystems by Bertuglia, Clarke, and Wilson (1994), I intend to reveal the sensitivity and resilience of a predetermined smart city narrative. To address these questions, the first step will be to understand what is meant by, and what constitutes, an urban system.

2. Defining Urban Systems

In this paper, an urban system will be defined as "a set of elements known as subsystems, that interact with each other through socio-economic and spatial mechanisms" (Bertuglia et al., 1994, p. 84). The subsystems identified by Bertuglia et al. include: Housing Market, Job Market, Service Sector, Land Market and Transport.

As shown in Figure 1, the main subsystems that constitute an overall urban system are complemented by what Bertuglia et al. call the "corresponding variables for describing the structure of an urban system," and are as follows: population, housing stock, industry, services,

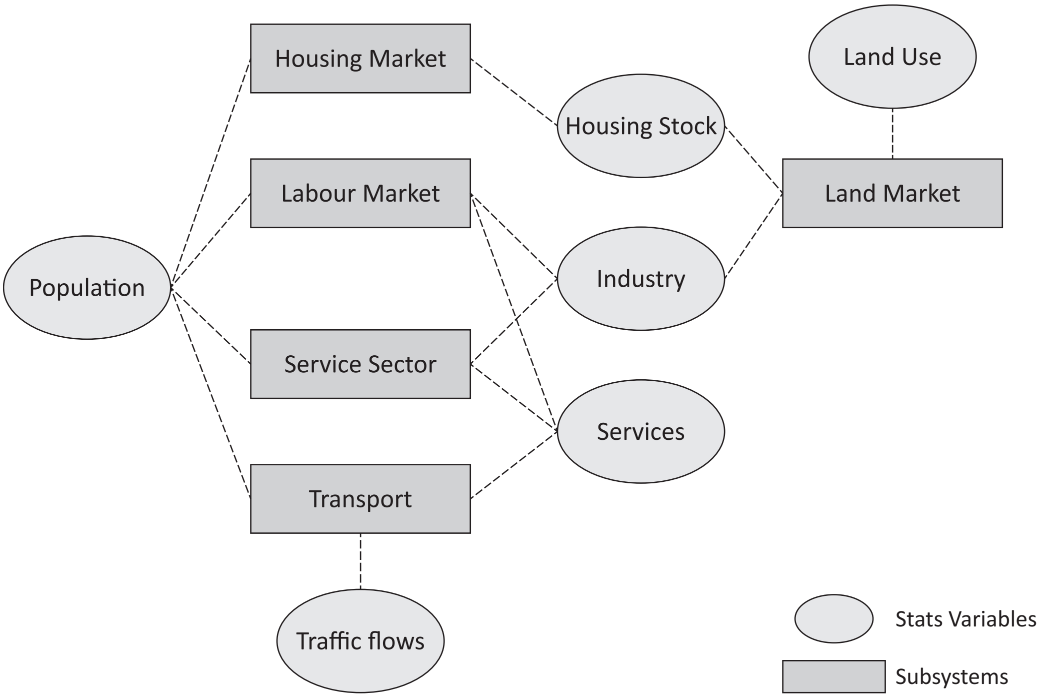

Figure 1. Urban system diagram of subsystems and corresponding variables. Source: Bertuglia et al. (1987, 1994).

land use, and traffic flows. From this diagram, a number of assumptions can be drawn: firstly, that subsystems are considered as separate entities; secondly, that corresponding variables play a vital role in their interrelations between all subsystems, and that interconnectivity occurs throughout the whole urban system; thirdly, that each singular subsystem is dependent/reliant on multiple relations between corresponding variables. Population is one of the most active variables when there are multiple variable interaction relations (as seen in Table 1) according to Bertuglia et al. (1987, 1994).

Although, what is not revealed by the diagram in Figure 1 or Table 1 is the influence of external forces or shocks on the interconnecting variables and subsystems themselves. As Tzaka, Kalogirou, Papakostas and Symeonidou (2010, p. 108) argue, "Urban systems, within and between contemporary cities, are driven by the dynamics of global economy, politics, climatic change, advanced technologies and increased mobility".

3. Ubiquitous-Eco-City of Songdo

Songdo, along with Cheongna and Yeongjong, were part of a vision to create a transnational space, Incheon Free Economic Zone (hereafter IFEZ). IFEZ, which is overseen by the Incheon Free Economic Zone Authority (IFEZA), established in 2002, was intended to be a new hub for the North-East-Asian regional economy to compete with established metropolises in the region, such as Singapore and Hong Kong (Figure 2). According to Sofia T. Shwayri (2013), the primary role of IFEZA, as the local authority charged with managing Songdo, was to court foreign investment and private partnerships to expedite the city from the concept stage to the reality of a twenty-first century global hub.

What is unusual about Songdo is that unlike any other Korean city it is managed by IFEZA, a governmental authority, but is 100% privately owned and funded. What makes this venture unique for Korea is that it is majority-owned by "foreign" companies. Gale International (hereafter Gale) owns a 60% share of the project, and the remaining proprietorship belongs to Morgan Stanley Real Estate (9%) and the large Korean steel company POSCO (30%). Songdo is also unusual in another respect, unlike earlier utopian visions of newly-planned cities, it was not envisioned as a response to the perils of overcrowding, as in the case of E. Howard and late-nineteenth-century Garden City movement following the industrial revolution. In a recent paper by Ayyoob Sharifi (2016), which traced the evolution of twentieth-century planning movements from the Garden City to Eco-Urbanism, prominent "urban visionaries"—from Ebenezer Howard to Lewis Mumford and Patrick Geddes—are viewed as motivated not only to address social problems (such as

Table 1. Urban systems variables reliance and relations table (Bertuglia et al., 1987, 1994).

Urban System		
Subsystems	**Subsystem Variable Reliance & Relations**	**Outcomes (Phenomena)**
Housing Market	Population (demand) and Housing stock (supply)	Residential mobility and house price
Labour Market	Population (supply) and Industries and Services (demand)	Service Location Dynamics
Service Sector	Population (supply) and Industries and Services (demand)	Service Location Dynamics
Transport	Population, Industrial and Service activities	Journeys to work, journeys to services, commodity flows, modal demand and network

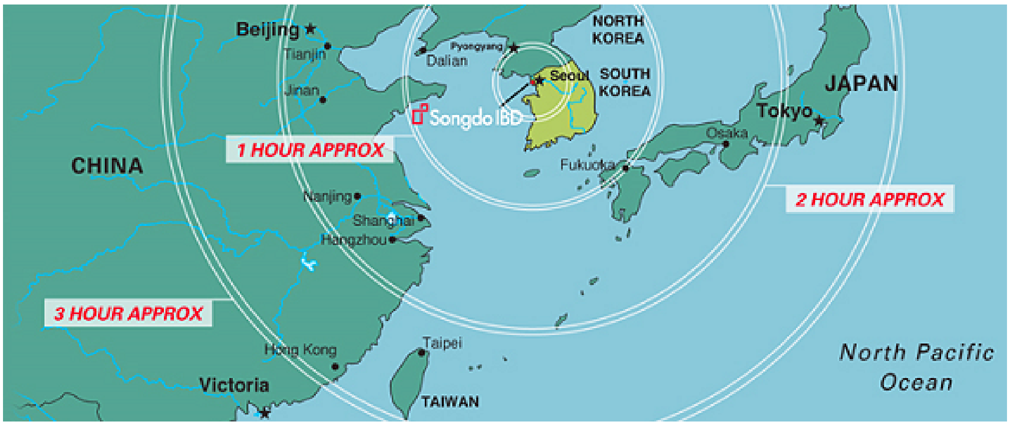

Figure 2. Location Map of Songdo (Songdo IBD from 2015), South Korea. Source: Gale International (2015).

housing shortages through constructing new planned communities), but also to create social reform (Sharifi, 2016, p. 4).

It has been well-documented that the Korean population will peak between 2020 and 2030, and, if low birth-rates continue, the population will reduce from 50 million to around 34 million according to lowest predictions. Thus, Songdo was not built to solve a housing crisis for the domestic population, but, rather, for global competiveness, foreign businesses and non-Koreans. A focus on global and foreign investors is central to Songdo's vision and underlined by the marketing strategy adopted by the cities developers Gale (Kim, 2010). This approach of focusing almost exclusively on external markets and investment is also reflected in the city layout through to the networked infrastructure, which Jung I. Kim argued is "anti-Korean"—"an imagined Euro-American urbanity distant from the existing urban characteristics of Seoul" (2014, p. 334). Indeed, the developers and IFEZ consciously decided to create a city that is collage of western cities; the main centrepiece of the city, central park, is inspired by New York City's Central Park. One of the key criticisms of Gale's design approach has been lack of attention to diverse social interests in favour of "aestheticizing the environment" and showcasing its infrastructure (Kim, 2014, p. 334).

Before 2008, the vision for Songdo was as a large scale Ubiquitous-City, marketed abroad as an international "city in box" by IFEZ as well as Gale (Shwayri, 2013). However, around 2008, a series of international events—such as the global financial crisis and the United Nations Climate Change Conference—meant that the vision for Songdo changed with a new political agenda for Green Growth. The global financial crisis meant that some buildings could no longer be built, and the level of anticipated foreign investment severely reduced. This forced IFEZ and its developers to adapt their original plan and focus on domestic markets.

2008 was also a time of great political change domestically in Korea, as President Lee Myun Bak's new government made significant changes to the previous administrative structure, which would directly shape the future direction of the ICT and Ubiquitous ICT growth strategies. This was also the year that Korea was invited to be part of the G20. Not content with being considered part of the global landscape, Korea, aimed to take on a leading international role. Indeed, global concerns about climate change in relation to the Kyoto Protocol and the designation of countries as either Annex I/II (Under Article 4.2 (g) of the Convention) and Non-Annex elevated Korea's position as an anomaly in the classification system to be viewed as "a reliable bridge between the advanced and developing nations" (Kalinowski & Cho, 2012, p. 4). At the G8 Extended Summit in Japan (2008), President Lee declared that Korea would voluntarily commit to Green House Gas emission reduction. With the model's appeal seemingly beginning to wane (as indicated by a lack of foreign investment by 2008), these global events acted as a catalyst in adapting the existing "U" model to satisfy the needs of foreign governments eager to find low-carbon solutions.

The global crisis of climate change then became the basis for Korea's next phase of ICT initiatives. In August 2008, President Lee announced that "low carbon green growth" would be central to combatting global warming and the economic crisis. He stated that Green ICT initiatives would become the new paradigm for economic and social development in Korea. The existing U-City model was then subjected to greening tactics as part of the newly-established Green Growth vision and was transformed into the "U-Eco-City". In relation to Songdo, as Yeon Mee Kim et al. (2009, p. 927) have noted, the intention then shifted to create a "sustainable city in which city management technologies based on ubiquitous infrastructure and the ecological system" ultimately formed an environmentally friendly city. Ubiquitous technologies were seen as ideal tools for showcasing "green technologies" in managing cities' energy efficiencies. The manipulation of the U-City concept proved useful as an attractive solution at time of global crisis to create a "U-Eco-City in a box". This was especially true for the developing Non-Annex I countries mindful of the climate change agenda and related financial-aid conditions, but looking to build new developments.

Apart from the rebranding of the Songdo as an "Eco-U-City" model, one of the most significant changes to impact the existing urban system in Songdo was the shift in target population. As discussed earlier, population in the urban system represents a significant variable in the systems structure due to its high level of interconnectivity within the urban system structure (subsystems and related variables). While the population projections appeared unchanged with a daytime commuting population of 300,000 and resident population of 253,000 (IFEZ, 2011), the demographic target had moved away from an overseas market to a domestic one. This shift would challenge the resilience of the overall system, as many facets of the physical networked infrastructure were already under construction.

With a need to coax local investment, domestic developers seized the opportunity to become a part of the new master plan for Songdo. From 2008, amongst the luxury LEED buildings that signified smart and future city living, apartments of the kind found throughout Korea, began to spring up where investment for empty parcels of land had fallen through. These residential apartments did not have the same LEED status as the intended and pre-2008 apartments and did not become part of Cisco's Smart+Connected framework—for marketing Songdo from 2009. To boost residential figures employees of one of the major shareholder companies, POSCO, were encouraged to take-up residency in Songdo. However, due to the apartments' high costs—some fifteen times the average annual household income in 2009 (Shin, 2009), Songdo was fast becoming a city for the wealthiest portion of Korean Society only.

The services that wealthy Seoulites had come to expect became problematic in Songdo due to high apartment prices, and lack of culturally specific amenities and services. For instance, the change in demographic target caused an increase in the demand for Korean restaurants, informal wet markets, childcare centres, and *hagwons* (private tuition institutes). Specifically, in relation to restaurant-service-based jobs, workers cannot afford to live in Songdo and are forced to endure long commutes for low pay using a transport system that is currently underdeveloped. Certainly, the affordability of eco-urban projects is a major problem. This concern has been also evidenced by other authors, such as Federico Caprotti (2014) and Caprotti, Springer and Harmer (2015), in relation to the case study of Dongtan eco-city near Shanghai. Elizabeth Rapoport's work (2014), which is a critique of how the term "eco-city" has been used historically additionally asserts that "affordable housing should all be considered as part of an eco-city framework" (Rapoport, 2014, p. 138). Additionally, Songdo's infrastructure cannot accommodate the informal wet markets that are commonplace in Korean cities. Indeed, conceptually, such informal markets, which are traditional and historical, do not represent the type of flagship future city that IFEZ wishes to project to the world.

Perhaps the most extreme example of the city's inflexibility of the infrastructure is Songdo's pneumatic waste collection systems. The networked pneumatic waste collection system below the streets of Songdo is connected to every planned commercial and residential dwelling with a focus on efficiency and carbon emission reduction to eliminate the need for rubbish collection trucks. On the streets of Songdo, public waste bins are inaccessible to non-residents because, to access them, you must have an official resident key (seen in Figure 3). This explicit indicator of Songdo's closed system has also caused problems for residents, as one IFEZ official informed the author (as part of an unstructured interview), on a recent tour of Songdo, that most people forget them, which means that rubbish accumulates near the bins. The bins themselves are also designed at a height and setback from the paths in a way that alienates, and makes them inaccessible to, wheelchair users.

Another attempt to boost domestic residential numbers has been orchestrated in the education sector, by the construction of new international schools and university campuses (both domestics and international). Such an approach has not been without its regulatory challenges and restrictions. According to Sonn, Shin, and Park (in press), there is normally a 40% cap on domestic students being enrolled in international schools; for example, this is the case in Seoul. However, regulations were relaxed pertaining to international primary and secondary schools in Songdo, which has resulted in the establishment of international independent schools such as Chadwick and Dulwich College (the main international schools in Korea and most showcased in Songdo's marketing literature). This policy is unlikely to develop social diversity as it will attract students from wealthier backgrounds and skew the socio-economic status of the urban system.

In the case of universities, Sonn et al. observed that creating "a new Korean university is still forbidden, but a new campus of an existing Korean university is allowed" (Sonn et al., in press, p. 10). As of 2016, three existing Korean universities have established secondary campuses in Songdo: Incheon University, Incheon Catholic University, and Yonsei University. For instance, from 2013, Yonsei has made it compulsory for all first-year students to attend and live on the Songdo international campus (IFEZ, 2014). Despite an influx of students, a lack of amenities that students are typically accustom to in Seoul has

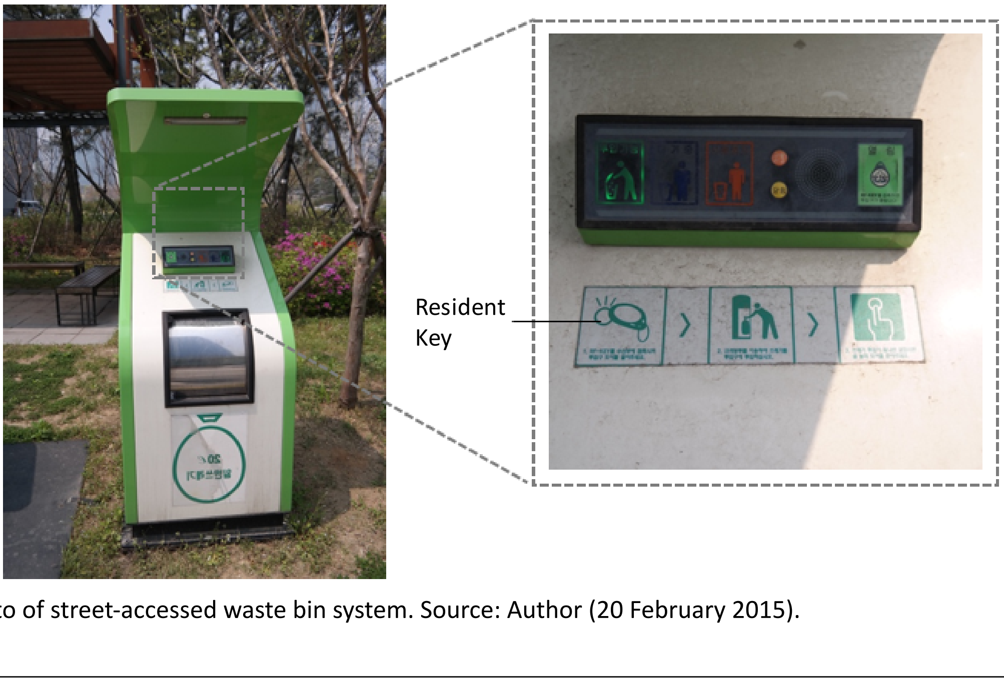

Figure 3. Photo of street-accessed waste bin system. Source: Author (20 February 2015).

meant that many students have elected to commute daily or stay in Songdo only from Monday to Thursday. Furthermore, as the higher education system in Korea includes five months of vacation periods, the university campuses are empty for almost half the year.

International universities have also been building in Songdo. Four universities have opened international campuses. Of these, three are American—University of Utah, George Mason University, and SUNY Korea (The State University of New York)—and one Belgian, Ghent University is the first European university campus.

Thus, it is apparent that higher education and low-paid jobs are some of the forces driving high numbers of domestic commuters who were unforeseen in the original model, which focused on international visitors. As the vision of a predominately international resident city diminishes, the inadequacy of transport has become increasingly apparent. For instance, the underground metro to Seoul takes around one and a half to two hours, and the route is via a change at Bupyeon Station in Incheon, as can be seen in Figure 4. The express bus service does offer a direct route from Gangnam in the southern part of Seoul, but the commute still takes at least an hour's time. Indeed, as going by car is more direct (Figure 5) and a preferred mode of transport, traffic has increased as well as travel times. One of the more visible consequences of this phenomenon has been a steady increase in the number of new petrol stations on route from Seoul to Songdo since 2014, but notably not within the showcase area of Songdo's International Business District. On the streets of Songdo bike lanes have been downsized and absorbed into green spaces to widen the roads to accommodate increased car traffic. Like most districts in Seoul, Songdo offers extensive underground parking, which is said to make the city feel more pedestrian friendly; yet, with an increased road width and number of lanes, the city's master plan is less pedestrian friendly then originally intended.

4. Technocratic Approach and Social Complexity

One of the main problems found from administering a technocratic approach at a city scale, as in the case of Songdo, is the ability to cope with the challenges of so-

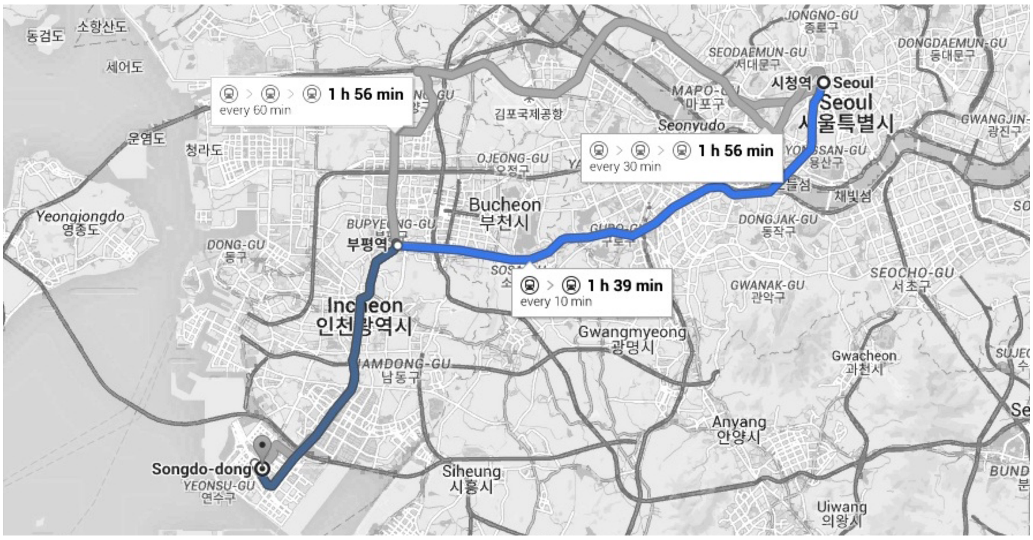

Figure 4. Commuting to Songdo by train. Source: Google Maps. Accessed December 2015.

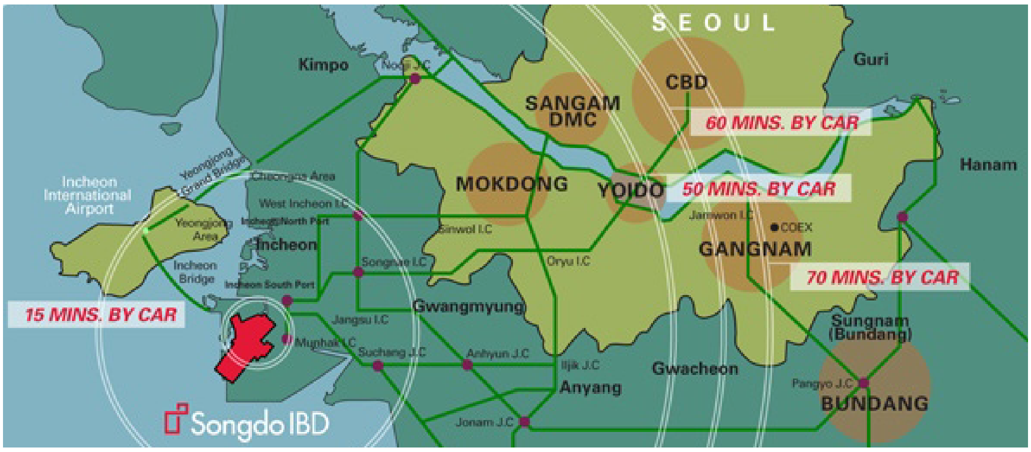

Figure 5. Commuting to Songdo by car. Source: Gale International (2015).

cial complexity. Although, the problem of addressing social complexity as part of an urban systems discourse is not a recent challenge and predates the current zeitgeist of smart cities. For instance, Ida R. Hoos's work on *Systems Analysis in Social Policy*, nearly half a century ago, noted that by adopting such an approach is to make "certain assumptions about the nature of the social problems and certain presumptions about the state of the art of systems techniques" (Hoos, 1969, p. 25). What is also implicit in such an approach according to Hoos is that the complexity of social systems can be "reduced to measurable, controllable units all of whose relationships are fully recognised, appreciated, and amenable to manipulation" (Hoos, 1969, p. 25). In reducing the complexity of social systems, a consideration of intangible factors is often overlooked, such as the role of cultural nuanced uses of space. However, such factors may not be recognized by the vocabulary of a city especially when the city is developed as part of a technology determined system.

In Songdo, the unintended demographic became the dominant population due to an unforeseen external global event. This event, not only disrupted the intended narrative of the city, but also brought to light the challenge of the citizens' role and the degree citizen agency afforded by the city developers (Gale), the technology vendors and IFEZ. In this sense, Songdo, rather than becoming the city of the future, as it was promised by its authors, was arguably repeating the same trajectory as past Modernist Utopia's such as Brasilia. In the case of Brasilia, for example, many commentators such as James Holston (1989) and Margit Mayer (2011), noted that although the main physical structure of the city reflected the planners original model of looking futuristic, "from a sociological and organization perspective, the way commerce was organized had more in common with medieval London" (Dills & Romiszowski, 1997, p. 26). It should be noted that, in the Korean context, such issues are not limited to cities built from scratch. For instance, along Tehran Ro, one of the main commercial streets in Gangnam, Seoul, there exists ongoing conflict between the traditional street vendors and the local authorities, who wish to sanitize the informal and culturally nuanced uses of space.

5. Conclusions

In a recent study, Mullins and Shwayri traced the evolution of Korea's green city paradigm and revealed how, "selling the U-City model was prioritized over a fully realized or conceptualized U-City model" (Mullins & Shwayri, 2016, p. 61). By examining Songdo from an urban systems perspective, this paper intended to unpack some of the challenges of using a green-city model-led and characterized by the same networked-technology that it is trying to showcase. The lens of the global financial crisis in 2008 revealed that the urban system in Songdo was not flexible and formulated as a closed system which underappreciated the impact of fluctuations and variability of external market forces. Unlike the cities that Songdo was supposed to rival—such as Hong Kong and Singapore—the closed system approach was constrained by a static conception of the role of foreign/local actors and relationship with the global markets. As Richard Sennet notes in his essay *The Open City: Closed System: The Brittle City*, "a closed system is meant to be integrated," and anything that wasn't part of the overall design is rejected or not registered by the system (Sennett, 2006). With a technologically deterministic approach to achieving efficiency and combating environmental issues, the U-City/U-Eco-City models are less sustainable in their in ability to cope with complexity. In relation to the latter, a closed urban system approach does not allow for the kind of "bottom-up" approach and citizen agency championed by early city commentators, such as Jane Jacobs and, more recently, in relation to the science of cities, Mike Batty. In the case of Songdo, and indeed for any new city built from scratch, an open system approach that is adaptable, can re-act and integrate non-intended inputs would be more resilient. Although Songdo is often considered unique as a case study by many scholars and commentators, the knowledge gained though this research—examining the adoption of a "closed system" approach—is transferable and, indeed, valuable to new cities and existing ones revising legacy infrastructure with smart city ambitions.

This paper has revealed how the whole urban system became vulnerable when one of the variables (population) diverted from the original plan. This deviation was against its developers and IFEZA's original model's that were intended for overseas markets. The shift towards a majority wealthy Korean domestic market has also revealed socio-spatial disparity, as well as inequality in accessing the city services in a system designed for formal inputs and outputs. Deregulation of educational policies, specifically in relation to international schools further compound the challenges of the urban system by only being accessible to the wealthiest members of Korean society. What this also revealed is how the change in population variable highlighted the shortcomings of the Songdo model. For instance, the individual subsystems—that constitute the whole urban system—were conceptualized through a technology-first approach, and, consequently, found insufficient in their ability to cope with the complexity and transience of "glocal" challenges facing cities today. The central focus of technology as the dominant vocabulary has obscured the attention required to address the social dimensions of a city and neglected the impact of external influences.

From an urban systems perspective, one of the recommendations of this study would be to identify local and culturally defined characteristics that could be used as a proxy to inform an empirical study on urban systems in Songdo. Future research would also benefit from a variable- or factor-led approach; such as a deeper examination of the role of informal socio-economic activities, as well as citizen agency. This shift in approach is intended to elucidate the impact on and variability of urban systems, and whether such phenomena are culturally nuanced by an indirect consideration of multiple case studies. In relation to the wider context, future research should consider the translation of global policies (such as those derived by the New Urban Agenda) into local and domestically nuanced policies. The qualitative approach of this research used a mixture of primary and secondary academic, government, NGO and private sector literature, as well as unstructured interviews, and first-hand experience of the city over a 5-year period. These materials were largely English-language sources and unstructured interviews. Thus, future research would benefit from a greater engagement with and inclusion of Korean language sources to provide a more rounded discourse.

In a forthcoming paper by Sonn et al. (in press), we are reminded that Free Economic Zones in South Korea can be traced back to the 1970s and that these were essentially seen as "export-processing zones" (Sonn et al., in press, p. 8) until the financial crisis of 1997. According to Soon et al., after 1997, there was a conceptual shift towards viewing these zones as "a symbol of deregulation." From recent research by Mullins and Shwayri (2016), it evident that in the case of IFEZ, Songdo is less an example of deregulation in the era of "Smart," but, rather, a twenty-first century reconfiguration of "export-processing zones," which showcases technology for export. Therefore, based on the research from this study, for Songdo to achieve its target of low carbon emissions, IFEZ will need to adopt a strategy that is sympathetic to both conceptions of Free Economic Zones to navigate between the changing domestic political climate as well as adaptable to global market shifts.

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Conflict of Interests

The author declares no conflict of interests.

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Article

Mobility as a Service: A Critical Review of Definitions, Assessments of Schemes, and Key Challenges

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Abstract

Mobility as a Service (MaaS) is a recent innovative transport concept, anticipated to induce significant changes in the current transport practices. However, there is ambiguity surrounding the concept; it is uncertain what are the core characteristics of MaaS and in which way they can be addressed. Further, there is a lack of an assessment framework to classify their unique characteristics in a systematic manner, even though several MaaS schemes have been implemented around the world. In this study, we define this set of attributes through a literature review, which is then used to describe selected MaaS schemes and existing applications. We also examine the potential implications of the identified core characteristics of the service on the following three areas of transport practices: travel demand modelling, supply-side analysis and business model design. Finally, we propose the necessary enhancements needed to deliver such an innovative service like MaaS, by establishing the state of art in those fields.

Keywords

business model; innovative mobility services; integrated mobility; modelling

Issue

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1. Introduction

In recent years, the increasing number of transport services offered in cities and the advancements in technology and ICT have introduced an innovative Mobility as a Service (MaaS) concept. It combines different transport modes to offer a tailored mobility package, similar to a monthly mobile phone contract and includes other complementary services, such as trip planning, reservation, and payments, through a single interface (Hietanen, 2014). This bundling of mobility modes presents a shift away from the existing ownership-based transport system toward an access-based one. It offers users a tailored hyper-convenient mobility solution, with a promising perspective to substitute private car.

Given its promising prospects, there is still a high degree of ambiguity surrounding the concept with multiple sources vying to offer definitions of MaaS, many of which may conflict with one another or deal with different aspects of the concept altogether. Additionally, although several MaaS schemes have been implemented around the world, there is a lack of assessment framework that classifies their unique characteristics in a systematic manner. "What constitutes a MaaS concept?"

is the central proposition of this study. To examine this proposition, we first attempt to define MaaS and the core characteristics based on a literature review. We build on earlier related works, such as Kamargianni, Li, Matyas and Schäfer (2016) and report our overview in Section 2. We then use these characteristics to review 12 selected MaaS schemes, presented in Section 3. This reveals certain differences and similarity trends among the schemes considered. It also grounds our theoretical characteristics of MaaS at an operational level and reveals certain attributes unique to a practical level. Next, we highlight the challenges to approach this emerging phenomenon of MaaS in Section 4, by examining the potential implications of the identified core characteristics of the service on the following three areas of transport practices: travel demand modelling, supply-side analysis, and designing business model. We review the state of the art in the three areas and explore the probable enhancements that will be required to deliver such an innovative and integrated mobility service. Finally, the paper is concluded in Section 5. The outcomes can be useful to pinpoint MaaS' core characteristics, derive a framework to assess MaaS schemes that fulfil to a certain degree this set of attributes and to indicate future challenges in transportation research.

2. Definition of MaaS

2.1. Existing Definitions

Mobility as a Service (MaaS) is a very recent mobility concept. It can be thought of as a concept (a new idea for conceiving mobility), a phenomenon (occurring with the emergence of new behaviours and technologies) or as a new transport solution (which merges the different available transport modes and mobility services). The first comprehensive definition of MaaS is offered by Hietanen (2014). He describes MaaS as a mobility distribution model that deliver users' transport needs through a single interface of a service provider. It combines different transport modes to offer a tailored mobility package, like a monthly mobile phone contract. This interpretation encompasses some of the core characteristics of MaaS: customer's need-based, service bundling, cooperativity and interconnectivity in transport modes and service providers. Cox (2015) adds to this definition, by emphasizing the similarity with the telecommunication sector. Being based on the same definition, Finger, Bert and Kupfer (2015) envisioned MaaS to integrate transport modes through the internet.

Holmberg, Collado, Sarasini and Williander (2016) emphasized the role of subscription in MaaS, giving the user the possibility to plan his/her journey, in terms of booking and paying the several transport modes that might be required, all in one service. To access the service, travelers will be asked to register or make an account. At a first level, this is to make booking and payment easier, as the concept envisions a 'seamless' combination of all transportation modes and a 'Mobility Aggregator' that gathers and sells all services through a single smartphone app, allowing easy fare payment and one-stop billing (CIVITAS, 2016). Based on the traveller's needs, he/she can have the choice of 'pay-as-you-go' or pre/post pay, considering his/her registration and a monthly subscription. At a second stage, subscription results in personalisation, framing mobility services around traveller's preferences, which is one important advantage that is absent from conventional public transport services and thus not covering passenger's needs which might result in inconvenience (Atasoy, Ikeda, Song, & Ben-Akiva, 2015). More specifically, tailoring the bundles to the heterogeneous needs of the subscribers (i.e. preferences in mode choice) is beneficial for both users and transport providers usually referred to as collaborative customisation or personalisation (Hietanen, 2014; Kamargianni, Matyas, Li, & Schäfer, 2015).

In addition to the definitions above, which emphasize the bundling and subscription aspects of MaaS, there are various other interpretations of the term that underscore other aspects. Atkins (2015) defines MaaS as a new way to provide transport, which facilitates the users to get from A to B by combining available mobility options and presenting them in a completely integrated manner. Thus, it is possible to consider MaaS as mobility service that is flexible, personalized and on-demand. Evidently, MaaS essential characteristic is the user-centric vision which frames the mobility service provision, a view which many authors strongly emphasize.

The key function of the internet and, more in general, of the technologies, has also been underlined in several definitions. Nemtanu, Schlingensiepen, Buretea and Iordache (2016) consider the Information and Communication Technologies (ICTs) as the main component of MaaS systems. They mention the collection, transmission, process, and presentation of the information necessary for identifying the best transport solution for user's needs. ICTs also play a vital part in information integration and convergence between users, providers, and services. The emergent notion in the Internet of Things (IoT), which further accentuate the connectivity between physical objects and virtual data, is a vision of Smart transportation systems to support the Smart City vision (Sherly & Somasundareswari, 2015). In the context of MaaS, similar emphasis stressing the importance of integrations between transport data, data infrastructure and physical transport infrastructure can also be observed (Hietanen, 2014). In Melis, Prandini, Sartori and Callegati (2016)'s interpretation, IoT acts as an enabler for the integration of private and public transport. Similarly, Giesecke, Surakka and Hakonen (2016) also considered an intelligent use of ICTs as the basis for transporting persons through the combination of different means.

By providing seamless travels with accessible and affordable solutions, MaaS has a perspective to contribute toward the strategic goals to achieve integrated multimodal systems, substituting private vehicles with alternative models (Chowdhury & Ceder, 2016; CIVITAS, 2016; Luk & Olszewski, 2003). Gould, Wehrmeyer and Leach (2015) envision MaaS as an opportunity to decarbonise transport sector by reducing the use of private cars and encouraging the diffusion of electric vehicles (EVs) within the city. Integrating transportation in a service like MaaS can shift the interest from private car usage to alternative modes counteracting the negative effect of current transport systems on urban contexts and the environment. However, Holmberg et al. (2016) point out the importance in setting MaaS tariff to ensure users' positive preference toward more sustainable modes, thus contributing to the sustainability vision.

Interestingly, Giesecke et al. (2016) conceptualize MaaS as a socio-technical phenomenon with sustainability as a critical aspect, thus shedding the light on the sociological level and the sustainability dimensions of the concept. This highlights the importance of users' acceptance and adoption to MaaS, as well as its roles to transform their habits and behaviours to meet their travel needs in a sustainable way. Accordingly, other authors consider sustainability and user perspective as the core elements of MaaS concept.

In the interpretation of König, Eckhardt, Aapaoja, Sochor and Karlsson (2016), MaaS offers need-based and customized mobility solutions for the users with the goal of achieving a more sustainable transport. This change of focus considers the social context to fulfil users' needs and environmental aspect while addressing the challenge of urban mobility. Implementing and delivering innovative services like MaaS will help to enhance accessibility and equity through a shift from ownership-based to access-based transportation. More specifically, a wide range of alternative modes and customized mobility services is expected to have societal value, increasing accessibility in reaching places and in the ability to utilize transport modes. Exploring the current use of shared-mobility, it is believed that these options can be the solutions for residents of low-density areas, as well as an affordable solution for low-income households (CIVITAS, 2016).

Other definitions considered the user-centred perspective from an operational point of view (Ghanbari, Álvarez San-Jaime, Casey, & Markendahl, 2015; Kamargianni et al., 2016; Rantasila, 2016). The main goal of MaaS systems is to provide seamless door-to-door mobility for users. This is made feasible by the technological advances, the cooperation of different operators, the bundling of several transport modes. Things have to be done in a smarter and more efficient way and by the full deployment of ICT and a stronger cooperation between public and private transport providers, Maas can result in a better allocation of resources and services, with the citizen as an end-user (Hietanen, 2014).

2.2. Proposed Core Characteristics of MaaS

Based on the literature review on definitions of MaaS in the previous section and further research about relevant innovative mobility services and ideas, we summarized the core characteristics that should be apparent when implementing such concept in practice. Table 1 presents those elements, without implying any hierarchical ranking.

3. An Overview of Existing MaaS Schemes

In this section, we present an overview of 12 selected MaaS schemes from around the world. Table 2 presents an analysis of these pilots and case studies that have been implemented in the context of MaaS and are described in accordance with the core characteristics defined in the previous section. Selecting these MaaS schemes was the outcome of a thorough review of literature and research. The list could be more extended than the one presented; we are aware of schemes such as Kätevä Seinäjoki (Seinäjoki, Finland), Mobility broker (Aachen, Germany), Mobility Mixx (Netherlands), Open Mobility (Berlin, Germany), Radiuz Total Mobility (Netherlands), Reisbalans (Netherlands), Stadtwerke PlusCard (Münster, Germany), Stuttgart-Services (Stuttgart, Germany), Swiss-Pass Plus (Switzerland), Switchh (Hamburg, Germany), Tripkey (Netherlands), Ylläs Around (Ylläs area, Finland), and other schemes included in MaaSiFie project (König et al., 2016) and Kamargianni et al. (2016). However, the scope of this paper highlights the importance of the main characteristics that should complement MaaS concepts and applications. Therefore, the selection process made necessary to exclude those case studies or pilots that lack the majority of this set of attributes, thus we present the schemes that were once conceptualized, designed and implemented covering at a certain degree most of these aspects.

The majority (eleven) of these schemes are from Europe and one from the United States. Eight of these are operational schemes, three are pilot schemes, and one is a scheme that was planned but cancelled before its operation even began (SHIFT). Three of these schemes have already ceased their operations. While there are large variations in the criteria, certain patterns can be observed. For example, public transport is nearly always included as part of the transport modes offered (eleven). Additionally, bike sharing (seven current, one planned), car sharing (eight current, one planned), and taxi (ten current, one planned) are included in most of these schemes. Certain schemes also include rental car (three), parking (six), and regional transport (six), as well as peer-to-peer car rental (one), and permit to congestion charging zone (one).

Other apparent trends: pay-per-use is mostly offered as a tariff option (seven), all schemes offer their platform through smart phone apps, while two schemes also provide web alternatives. Next, most services provide real-time information, trip planning, booking, ticketing, and payment functionalities. Some also include perks, such as push information for service alerts, integrated invoice, access to municipality services, freight services

Table 1. Description of MaaS' core characteristics based on literature review.

Core Characteristic	Description
1. Integration of transport modes	A goal of MaaS schemes is to encourage the use of public transport services, by bringing together multi-modal transportation and allowing the users to choose and facilitating them in their intermodal trips. Following transport modes may be included: public transport, taxi, car-sharing, ride-sharing, bike-sharing, car-rental, on-demand bus services. Envisioning a service beyond the urban boundaries, it will embrace also long-distance buses and trains, flights, and ferries.
2. Tariff option	MaaS platform offers users two types of tariffs in accessing its mobility services: "mobility package" and "pay-as-you-go". The package offers bundles of various transport modes and includes a certain amount of km/minutes/points that can be utilized in exchange for a monthly payment. The pay-as-you-go charges users according to the effective use of the service.
3. One platform	MaaS relies on a digital platform (mobile app or web page) through which the end-users can access to all the necessary services for their trips: trip planning, booking, ticketing, payment, and real-time information. Users might also access to other useful services, such as weather forecasting, synchronization with personal activity calendar, travel history report, invoicing, and feedback.
4. Multiple actors	MaaS ecosystem is built on interactions between different groups of actors through a digital platform: demanders of mobility (e.g. private customer or business customer), a supplier of transport services (e.g. public or private) and platform owners (e.g. third party, PT provider, authority). Other actors can also cooperate to enable the functioning of the service and improve its efficiency: local authorities, payment clearing, telecommunication and data management companies.
5. Use of technologies	Different technologies are combined to enable MaaS: devices, such as mobile computers and smartphones; a reliable mobile internet network (WiFi, 3G, 4G, LTE); GPS; e-ticketing and e-payment system; database management system and integrated infrastructure of technologies (i.e. IoT).
6. Demand orientation	MaaS is a user-centric paradigm. It seeks to offer a transport solution that is best from customer's perspective to be made via multimodal trip planning feature and inclusion of demand-responsive services, such as taxi.
7. Registration requirement	The end-user is required to join the platform to access available services. An account can be valid for a single individual or, in certain cases, an entire household. The subscription not only facilitates the use of the services but also enables the service personalisation.
8. Personalisation	Personalisation ensures end users' requirements and expectations are met more effectively and efficiently by considering the uniqueness of each customer. The system provides the end-user with specific recommendations and tailor-made solutions on the basis of her/his profile, expressed preferences, and past behaviors (e.g. travel history). Additionally, they may connect their social network profiles with their MaaS account.
9. Customisation	Customisation enables end users to modify the offered service option in according to their preferences. This can increase MaaS' attractiveness among travelers and its customers' satisfaction and loyalty. They may freely compose a specified chained trip or build their mobility package with a different volume of usage of certain transport modes to better achieve their preferred travel experiences.

(planned), and real-time congestion monitoring. Additionally, a third party is the service aggregator for the majority of these schemes (seven), three other schemes have PT-providers as their aggregators and two rely on their local authorities. All of them utilised GPS technology, nine cases employ ePay, two offer smart card for payments and one eWallet, which can also be used to pay for other services.

While several apps allow unregistered users to use basic functionalities like route planning, all of them required users' registration to access the service, make a booking and customise the service to their needs. More variations can be observed across the personalisation and customisation criterion. Still, certain common features, such as storing of past or favourited trips and selection of preferred modes can be discerned.

In addition to the core characteristics identified in Table 2, we established three MaaS attributes through the review of case studies, they are:

1. **Decision influence**—Certain MaaS schemes have features to influence users' trip decisions, ranges from a less active approach, such as SMILE's comparison of CO_2 emission by each mode to a more active approach in UbiGo, which promotes PT mode, and an incentive-based of Whim, which re-

Table 2. Summary of MaaS schemes reviewed in this study.

Scheme (Area)	**TransitApp** (USA, UK, Canada, Europe, Australia)	**Optymod** (Lyon, France)	**Mobility 2.0 services** (Palma, Spain)	**SHIFT—Project 100** (Las Vegas, USA)	**UbiGo** (Gothenburg, Sweden)	**Mobility Shop** (Hannover, Germany)
Status (Year)	Operational (2012–)	Operational (2012–)	Pilot (2013–)	Planned (2013–2015)	Pilot (2013–2014)	Operational (2014–)
Transport modes and related services	PT (Inc. local ferry) Bike sharing Car sharing Taxi Ride-hailing	PT Bike sharing Regional train Parking	PT Bike sharing Taxi	Bike sharing Car sharing Taxi Shared shuttle	PT Bike sharing Car sharing Car rental Taxi	PT Car sharing Taxi Regional trains
Tariff option	Pay-per-use	None	Pay-per-use	Monthly tariff	Monthly tariff	Fixed monthly membership to access discounted tariff
Platform	App/Web	App	App/Web	App	App	App
Available functionalities	Real time info. Trip planning Booking (shared modes/Taxi) Payment (bike sharing) Service alerts Departure alarms Stop notifications	Real time info. congestion Prediction Trip planning Booking (bike sharing) Service alerts Plane's arrival-departure time info	Real time info. Trip planning Service alerts Real time congestion monitor	Trip planning Booking Payment Invoicing	Trip planning Booking Ticketing Payment Invoicing 24hr customer service phone line	Real time info. Booking Ticketing Payment Invoicing Service alerts
Type of actors involved ***Service aggregator***	Public and private actors *3rd party*	Public actors *Local authority*	Public and private actors *Local authority*	Private actor *3rd party*	Public and private actors *3rd party*	Public and private actors *PT provider*
Use of technologies	GPS / ePay (bike sharing only)	GPS	GPS	GPS / ePay	GPS / Smart card	GPS / ePay / Smart card
Demand orientation	Yes	Yes	Yes	Yes	Yes	Yes
Registration requirement	Yes, for booking and customisation	Yes, for customisation	Yes, for booking and customisation	NA	Yes, for usage and customisation	Yes, for usage and customisation
Personalisation	Store regular and preferred routes Saved location	Input personal address, preferable modes, and ownership of bicycle	Store favourite trips	Automatically Optimised trip planner	NA	Store favourites trips and recall previous trip
Customisation	Minimised walking option Disabled certain service/modes Link with calendar and personal contact	Select service subscription for news	Enable certain map sections and accessibility map people with special needs	Mobility budget with Top-up	Mobility budget with Top-up and roll over	Possibility to create individual mix of transportation Booking and payment cancelation

Table 2. Summary of MaaS schemes reviewed in this study (continued).

Platform **(Area)**	**Smile** (Vienna, Austria)	**Tuup** (Turku Region, Finland)	**My Cicero** (Italy)	**Moovel** (Germany)	**Whim** (Helsinki, Finland)	**WienMobil Lab** (Vienna, Austria)
Status **(Year)**	Pilot (2014–2015)	Operational (2015–)	Operational (2015–)	Operational (2016–)	Operational (2016–)	Based on Smile project (2015–2016)
Transport modes and related services	PT (e-)Bike sharing (e-)Car sharing Taxi Parking garages Charging stations Regional trains and ferry	PT Bike sharing Car sharing Car rental P-2-P car rent Taxi and shared taxi Parking rent Freight service*	PT Taxi* Parking spaces Permit for urban congestion charging zone Regional rail and bus	PT Bike sharing Car sharing Taxi Ferry Regional rail	PT Rental car Taxi Regional rail Bike sharing* Car sharing*	PT Bike-sharing Car-sharing Taxi Parking garages
Tariff option	Pay-per-use	Pay-per-use	Pay-per-use	Pay-per-use	Three monthly packages and pay-per-use	Pay-per-use
Platform	App	App	App	App	App	App
Available functionalities	Real time info. Trip planning Booking (shared modes / Taxi / Regional train) Ticketing Payment Invoicing Service alerts	Real time info. Trip planning Booking Ticketing Payment (for PT, taxi, and shared taxi)	Real time info. Trip planning Booking Ticketing Payment Invoicing Municipality services	Real time info Trip planning Booking Ticketing Payment Invoicing	Real time info. Trip planning Booking Ticketing Payment Invoicing	Real time info. Trip planning Booking Payment Invoicing
Type of actors involved ***Service aggregator***	Public and private actors *PT provider*	Public and private actors *Third party*	Public and private actors *Third party*	Public and private actors *Third party*	Public and private actors *Third party*	Public and private actors *PT provider*
Use of technologies	GPS / ePay	GPS / ePay (PayiQ)	GPS / ePay / e-Wallet	GPS / ePay	GPS / ePay	GPS / ePay
Demand orientation	Yes	Yes	Yes	Yes	Yes	Yes
Registration requirement	Yes, for usage and customisation	Yes, for usage and customisation	Yes, for usage and customisation	Yes, for usage and customisation	Yes, for usage and customisation	Yes, for booking and customisation
Personalisation	Optimised trip plan to user's profile (i.e. annual ticket, subscription and membership)	Optimised travel plan based on user's daily agenda	Store types of ticket Record and share journey	Store favourites routes Personalised notification on disruptions	Calendar synchronization Personal info sharing Social interaction	Save personal mobility profile Store car & bike sharing membership
Customisation	Enable mode filtering based on cost, time, and CO_2 footprint	Preferred modes, based on cost and CO_2 footprint	Preferred modes and payment Top-up	Link with social media accounts Booking cancellation	Cancelation Change of subscription Top-up	Preferred modes, based on cost, time, and CO_2 footprint

Note: *Planned service.

wards users for their 'green' trips. These features can be beneficial in ensuring MaaS positive contribution to sustainability. On the other hand, it also points toward a need for a monitoring system to ensure that such feature is utilized for societal benefits.

2. **The inclusion of other services**—SMILE included access to parking, park and ride service, e-vehicle, and regional ship demonstrates the result of including a broad range of stakeholders in MaaS. Tuup's inclusion of Piggybaggy, a crowdsourcing freight transport service and My Cicero's municipality services are also unique examples how MaaS can open the possibility for other transport related services.
3. **Mobility 'currency'**—Whim is the only scheme considered here that employs this feature, which can be a step toward a truly integrated multimodal transport system. It enables users to customise their monthly mobility budget to best suit their preferences and not 'locked in' by any sunk cost, such as annual PT subscription or car rental membership. On the other hand, it also increases platform provider influence toward pricing of service. A Whim point purchase through its most expensive subscription (389€ for 10,000 points) is more than 50% cheaper than a Whim point purchase through its most basic package (89€ for 1,000 points). The economy of scale of such basic commodity can have implications on equity aspects.

4. State of the Art and Future Challenges with MaaS

In this section, we examine the perspective implications of MaaS based on our proposed core characteristics in three areas of transport practice: travel demand modeling, supply-side analysis, and designing business model.

4.1. Demand-Side Modelling

Transport modelling is important and essential for estimating travel demand and offering valuable information to policy makers and transport planners. During the years, several modelling approaches have been explored and formulated. In travel demand modelling, conventional models were aggregate in nature and the dominant approach was the four-step modelling process. Dissatisfaction with trip-based models, policy needs for detailed sociodemographic information for the trip at individual/household level but mostly the behavioural inadequacy of this approach has led to the emergence of disaggregate forecasting models (Bhat & Koppelman, 1999). Both supply and demand models have evolved from static to dynamic capturing travel behaviour in terms of time-dependent conditions and information, and from an aggregate to a disaggregate representation of travel, focusing on the heterogeneity of individual traveling (Ben-Akiva, Bottom, Gao, Koutsopoulos, & Wen, 2007).

Moving to activity-based approach, new aspects are of crucial importance: integrity, interdependencies between trips of the same trip chain or household, higher temporal and spatial aggregation and a strong behavioural basis, as engaging in an activity in fact 'represents' a dynamic interaction of household needs, tasks, and constraints (Rasouli & Timmermans, 2014a). One of the first types of activity-based models were the constraints models, examining the feasibility of agendas with a great emphasis on the role of spatial-temporal constraints on daily travel behaviour. Then, the second approach in activity-based modelling was the econometric one, based on discrete choice models and on the principle of utility maximisation to model pattern formation. Following those, rule-based models (also known as computational process models) have developed, creating activity schedules based on heuristics and decision rules. However, more extended approaches have emerged including time-space prisms and constraints and agent-based modelling (Bhat & Koppelman, 1999; Timmermans, Arentze, & Joh, 2002).

All these activity-based model systems have been built upon the assumption that travel decisions are made under conditions of certainty. This hypothesis can be considered not realistic, as the state of transportation systems is affected by a variety of uncertainty factors and decision makers don't have a perfect knowledge about their choice set. So, in order to improve the accuracy and reliability of such models, interesting theories and models of human choice and decision-making under risk and uncertainty have been explored and developed in travel behaviour analysis (Rasouli & Timmermans, 2014b). Among these, prospect theoretic models (Kahnema & Tversky, 1979) and regret-based models (Chorus, Arentze, & Timmermans, 2008) are gaining an interest in travel behaviour research in recent years, serving as a valuable alternative to the dominant utility-maximisation models. The introduction of uncertainty in the decision-making process should be accompanied by the identification and exploration of other drivers of travellers' choice behaviours, which must be considered in modelling travel demand for innovative mobility services like MaaS in the dynamic and complex context of the smart city.

MaaS is a user-centered service adopting the advances of technology and ICT to offer various mobility solutions to customers, conceptualising travel differently. In this new context, people will have a wide list of options to choose from, based on public and private transport modes, multiple needs and preferences, and a service which allows them to pursue more activities within the same timeline (multitasking). Activity-based modelling techniques are considered crucial for understanding how individual and households organise their daily activities. At the same time, ICT and smartphones have contributed positively to models used to predict the sequence between activity and travel episodes. However, attempting to deliver innovative services like MaaS, requires extensions in current activity-based modelling, considering the more dynamic context of modern lifestyle, social influence, ICT, responses to travel recommendation systems, attitudes and subjective considerations and the increasing degree of uncertainty. Thus, a critical reflection on how to expand current activity-based models and their underlying theories and choice models is needed to better capture the comprehensive nature of the travel behaviour and decision-making process related to MaaS. Other theories and models originally formulated in different fields, like marketing, behavioural economics, social psychology and technology and innovation, might be explored for their appropriateness in modelling the demand side of MaaS.

To the best of our knowledge, as Maas is an emerging trend and its implementation in the real world is still limited, there is a very small number of studies examining the travel demand modelling for MaaS. Sochor, Strömberg and Karlsson (2014, 2015) studied the changes in travel behaviours, users' mode choices and level of satisfactions by collecting and analysing data on a six-month field operational test of UbiGo. Data was collected from participating and non-participating households, throughout a mixed-methods approach, to identify the interests and the obstacles for joining UbiGo. Results reveal the main motives of adopting and using MaaS (i.e. curiosity, convenience, flexibility) and how they change over time. Findings also indicate that the participants could be considered as innovators or early adopters, confirming the need to integrate innovation theory in travel demand modelling applied to MaaS. Afterward, Sochor, Strömberg and Karlsson (2016) focus on the application of Roger's diffusion of innovation theory as a useful tool for travel behaviour change in a sustainable direction.

In their study about the development of a mobility assistance system, Hilgert, Kagerbauer, Schuster and Becker (2016) develop a new activity-generation module in the agent-based, microscopic travel demand model mobiTopp (Mallig, Kagerbauer, & Vorisch, 2013) to gain insights about changes in travel behaviour and daily mobility patterns due to the use of customized mobility services. This model used a utility function base on user's favourite criteria (e.g. time, cost, and, preferred modes of transport). Binomial and multinomial logit models were estimated to analyse activity and travel related decisions at different steps, using the data of the German Mobility Panel (MOP) (Hilgert et al., 2016). The implementation of this travel demand model is still ongoing, but it is expected to quantify the effects of mobility assistance on individual daily travel behaviour and travel demands.

As underlined by the European Commission (2016), existing quantitative studies on MaaS impacts on users travel behaviour are not yet developed. For a better understanding of this emergent phenomenon and its implications, studying and modelling user's acceptance factors and travel-related choices represent an urgent area for further research.

4.2. Supply-Side Modelling

The supply side focuses on the modes of transport offered and covers both design and operations. The impact that MaaS has on the supply side can be perceived in the early name that this concept was given in the EU policy scene in 2009: the "Fifth Mode" (Schade, Krail, & Kühn, 2014). There are different reasons why MaaS represents such a disruptive concept for the supply side despite aiming "merely" at a complete integration of the existing modes of transport, and we aim at mentioning the most relevant ones.

The integration that MaaS represents has been triggered by the number and variety of new on-demand transportation services that have appeared in the transportation arena. Among these services, we encounter shared services, namely car-sharing and bike-sharing. The one-way configuration of these shared services (the car or bike can be left at the destination and not necessarily at the initial pick-up point), is the one that allows for more flexibility and, therefore, the most suitable for MaaS. The major challenges in designing such services are vehicle fleet optimization and relocation strategies (Cepolina, Farina, & Pratelli, 2014). A step forward needed to bring them further under a MaaS ecosystem would be to take the integrated MaaS supply network into account in these relocation strategies. The effect of autonomous vehicles is another aspect that needs to be considered and that will ease relocation efforts. Research suggests that autonomous cars can rebalance themselves in the network and coordinate their actions at a system-wide level (Zhang, Spieser, Frazzoli, & Pavone, 2011), solving some of the possible system level problems of car-sharing and Litman (2017) suggests that automatic car-sharing/taxi schemes will become a reality in 2030-40s suggesting a positive impact of automated vehicles on MaaS.

Other on-demand transportation services that will play an important role in MaaS are demand responsive on-demand services. They can be classified into individual services, such as regular taxis or Uber-like services, and collective services (e.g. Kutsuplus and Uberpool). The major challenge in modelling this kind of services lies in designing the routing strategy for the vehicles. The routing algorithm to deal with this routing problem has been widely studied and is known in optimisation as the dial-a-ride problem (DARP), which is a generalisation of the Travelling Salesman Problem (TSP). Heuristic search algorithms have been proven to provide optimal solutions for these problems. To control and plan the requests with the desired level of service in the pick-up and drop-off times, the supplier uses the time window approach, as studied, for example, in (Mahmoudi & Zhou, 2016). As an extension of the DARP, the Integrated Dial-a-ride Problem (IDARP) includes the integration of demand responsive services with fixed route services. This mode integration scheme shows how the combination of different modes of transport can improve the transportation network by exploiting the benefits of each service, as it is aimed at in MaaS ecosystems. The optimisation objective of such integration focuses on maximising passenger utility (Wilson, Weissberg, & Hauser, 1976), maximising the service capacity (Liaw, White, & Bander, 1996), or any other operational or service related aspect.

Further than the mentioned IDARP, which focuses on the integration of demand responsive services and fixed route service only, the intermodal mobility planning needs to consider all available services. Currently, it is mainly approached applying concepts from the realm of graph theory and constraint-satisfaction-problems (Masuch, Marco, & Keiser, 2013), but available research on this topic is still limited.

Even if the integration of transport modes is the first requirement in MaaS schemes, payment integration and ICT integration are also main components in the supply integration that MaaS offers, as it has also been reported by Kamargianni et al. (2016). Regarding payment integration, smart cards have been its main enabler. Smart cards offer a large amount of information that can be used both in the planning and operation stages. Nevertheless, better algorithms are still needed to validate the data, and new modelling methods will be needed, such as the Totally Disaggregate Approach, to deal with the high detailed level of resolution provided by these information sources (Pelletier, Trépanier, & Morency, 2011). MaaS enablers will need to consider these aspects since the integration of all available modes will intensify these problems. The longitudinal data provided by these integrated payment methods can be used to better understand travel patterns and better localise the critical points for the supply-demand optimisation. Privacy of data is another principal source of concern about the smart card (and alike) payment methods (Dempsey, 2008). More recently, mobile payments (considered as virtual smart cards) are also being studied (Di Pietro, Guglielmetti Mugion, Mattia, Renzi, & Toni, 2015).

Integration of modes and the payment for their usage would not be useful in MaaS if the whole information of these services were not readily available. This is why the advancements in ICT platforms are a major aspect in the development of MaaS systems. The integrated and real-time multimodal information provided to the traveler can update a traveller’s perception of the travel alternatives dynamically (Chorus, Molin, & Van Wee, 2006) and challenge the perceptions of their perceived utility related to non-car modes (Kenyon & Lyons, 2003), inducing modal shift. This information is acquired from unifying very different types and sources of the data, and the data aggregation is still one of the main technical challenges when dealing with intermodal algorithms (Masuch et al., 2013). The integration of information is of vital importance and a pillar in MaaS: it is what the end user receives and upon which the whole supply network builds upon. Other than that, good governance and business models need to be assured to ensure the correct functioning of such a complex system.

4.3. Governance and Business Model to Match Supply and Demand

An implementation of MaaS can have significant impacts to the existing business model of public transport, especially on the level of integration. An increase in the required level of integration can pose a dilemma for public transport providers in their decisions related to integration with other operators. Traditionally, public transport services are usually provided by monopoly or multi-service providers benefiting from economies of scope and scale (Viton, 1992; Farsi, Fetz, & Filippini, 2007). Apart from the conventional provision of services and its pros and cons, public transport providers might benefit from MaaS, which seems an advanced version of integrated public transport services. Technically, integration of services may be realised by using so-called platform technology, which facilitates interactions between travellers and suppliers of transport services in an improved or smarter way (Ballon, 2009; Gawer, 2014). Economists perceive platforms as markets which mediate transactions across different customer groups or ‘sides’. Multi-sided platform (MSP) is a model for MaaS. Besides few practical examples to date, experience can be gained from other industries such as ICT, telecommunications, and airlines industry (Hagiu & Wright, 2015).

A crucial characteristic of MSP is the presence of the network externalities (also known as network effects and demand-side economies). Direct and indirect externalities are two types of network effects (Shapiro & Varian, 1999). *The direct network effect* is that utility of a product increases by growing number of users on the same side of the platform, usually for product interconnecting people such as communication technologies (i.e. telephone, e-mail, games). *The indirect network effect* is defined as an effect in which an increase in the number of users on one side is beneficial to other sides of the platform. The indirect effects that arise between users and developers of games stem from two sources: 1) a membership effect, which members on one side enjoy greater benefits of having more members on the other side to potentially transact with, independent of the nature of the product and 2) a usage effect, which users have greater benefits from using better complementary products (Rochet & Tirole, 2003).

Additionally, platforms create value by coordinating these services through providing information about the prices and qualities of the services. For example, Uber offers a platform that matches travellers demanding a trip and car owners that want to supply this trip (Gawer, 2014; Hagiu, 2014). MSPs reduce search and transaction costs. Search costs are costs incurred by the multiple sides before they interact, to determine the best “trading partners.” (Hagiu & Wright, 2015). Nevertheless, there are certain challenges in establishing a platform, such as the chicken and egg problem (getting both sides to use the platform) and gaining a critical mass of users on both sides in the right proportions to guarantee acceptable added-value and sustainable growth of platforms (Hagiu, 2014; Jullien & Caillaud, 2003).

Few studies investigated the application of MSP in public transport. Finger et al. (2015) explain the concept of MaaS with practical examples. Their evaluation covers the challenges in operationalising mobility platforms, including getting a critical mass and regulatory challenge to provide a market opportunity for platforms. Sochor et al. (2015) discuss the matches and mismatches of customers' expectations with delivered services during experimenting UbiGo. Although the project's expectations were met on increased of transport options, easier payment, tracking expenditures, and reduced need for private car ownership, there are also several mismatches. Firstly, the revenue generated by the service was below expectation. This is due to the below-than-expected car rental and car sharing services usage by its users. Additionally, regulation on the reselling of PT service prevented UbiGo from purchase PT services and make a profit of them. Secondly, the users needed to pay a minimum amount in advance and they perceived it less flexible. A study by Meurs & Timmermans (2017) define and discussed the features and challenges for successful implementation of MSP. They explain the concept of network externalities as an important feature of MSP. Increasing the number of car shares make the platform more attractive for other users (direct network effect) and If more transport providers join the platform, the utility of travellers will increase due to more options being offered (indirect network effect). Additionally, the chicken-and-egg problem and achieving the critical mass are mentioned as challenges in implementing MSP in PT. König et al. (2016) define business ecosystem of MaaS and develop a framework to value chain of different MaaS schemes. A similar work is done by Kamargianni & Matyas (2017), classifying different actors based on the relationships with MaaS providers. They conclude that the distribution model of MaaS differs from the prevalence way of mobility services' provision which is one of the distinctive features of MSP. The MaaS providers aggregate the offering services by mobility providers. Thus, MaaS is not only about the integration of mobility services, but also requires a complete restructuring of the supply chain of mobility service providers.

5. Conclusion

The novelty and fuzzy natures of MaaS make it a challenge to ascertain what MaaS is, its implications and how to address them. We distilled a set of core characteristics of MaaS from a literature review and used this to present an overview of selected MaaS schemes that fulfil more or less these elements. The review reveals that while there is a diversity in attributes, such as personalisation, customisation, tariff options and platform aggregators, certain patterns can be observed among the schemes considered, such as the modes included in the services, available basic functionality (real time information, trip planning, booking, and ticketing) and employed technologies (GPS, E-ticket, and E-payment). It also appears that certain schemes go further to offer perk features, such as trip disruption warning and synchronization with personal agenda.

The assessment also reveals certain attributes unique to case studies, such as features that can influence trip decision, the inclusion of other services, such as freight transport and municipality services, and the use of a mobility currency. These characteristics may add to enhance the proposed framework but requires additional case studies to confirm if they are essential parts or perks of MaaS.

We then look at the possible implications of these core characteristics toward demand modelling, supply modelling, and governance in transport practices. We established the state of art in the mentioned fields and proposed the probable enhancements needed to deliver such an innovative service like MaaS. Our suggestions include extensions in current activity-based modelling, improvements in optimisation of vehicle fleet and routing for DRT, and enhancements on integrations, among others. We also point out challenges in the implementation of the multi-sided platforms, such as chicken and egg problem and achieving a critical mass of user.

The findings in this study provide a point of reference for MaaS definition, a description framework of relevant schemes, and a direction toward further works in the three areas. It should also be relevant to other researches or activities related to Mobility-as-a-Service. Additional enhancements to this analysis can be made by adding more schemes into the description framework, which can further reveal differences, similarities, and unique characteristics of the services.

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Conflict of Interests

The authors declare no conflict of interests.

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Article

Investigating the Potential of Ridesharing to Reduce Vehicle Emissions

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Abstract
As urban populations grow, cities need new strategies to maintain a good standard of living while enhancing services and infrastructure development. A key area for improving city operations and spatial layout is the transportation of people and goods. While conventional transportation systems (i.e., fossil fuel based) are struggling to serve mobility needs for growing populations, they also represent serious environmental threats. Alternative-fuel vehicles can reduce emissions that contribute to local air pollution and greenhouse gases as mobility needs grow. However, even if alternative-powered vehicles were widely employed, road congestion would still increase. This paper investigates ridesharing as a mobility option to reduce emissions (carbon, particulates and ozone) while accommodating growing transportation needs and reducing overall congestion. The potential of ridesharing to reduce carbon emissions from personal vehicles in Changsha, China, is examined by reviewing mobility patterns of approximately 8,900 privately-owned vehicles over two months. Big data analytics identify ridesharing potential among these drivers by grouping vehicles by their trajectory similarity. The approach includes five steps: data preprocessing, trip recognition, feature vector creation, similarity measurement and clustering. Potential reductions in vehicle emissions through ridesharing among a specific group of drivers are calculated and discussed. While the quantitative results of this analysis are specific to the population of Changsha, they provide useful insights for the potential of ridesharing to reduce vehicle emissions and the congestion expected to grow with mobility needs. Within the study area, ridesharing has the potential to reduce total kilometers driven by about 24% assuming a maximum distance between trips less than 10 kilometers, and schedule time less than 60 minutes. For a more conservative maximum trip distance of 2 kilometers and passenger schedule time of less than 40 minutes, the reductions in traveled kilometers could translate to the equivalent of approximately 4.0 tons CO_2 emission reductions daily.

Keywords
emission reductions; ridesharing; spatiotemporal data mining; trajectory clustering; trajectory mining

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1. Introduction

Historically, transportation systems improved personal mobility and defined the spatial extent of cities. With advancements in transportation technologies, rising land costs, and growing urban populations, people now make more and longer trips. However, this increased mobility also increases local air pollution, greenhouse gas (GHG) emissions, and congestion. Globally, the transport sector accounted for 17% of total CO_2 emissions in 2013: a share that is growing (European Commission, 2016). With increased mobility of growing urban populations, global emissions from the transportation sector are likely to increase in lock step (Organization for Economic Cooperation and Development [OECD], 2011).

In China, the number of on-road vehicles increased dramatically over the past few decades. In response, the national government implemented stringent vehicle emission standards. Several studies have focused on evaluation of the emission factors of various vehicle types in Chinese cities over the past decade (Hu et al., 2012; Huo et al., 2012; Liu, He, Lents, Wang, & Tolvett, 2009; Wang, Westerdahl, Wu, Pan, & Zhang, 2011; Wang et al., 2012; Wu et al., 2012; Zhang, Wu, Liu et al., 2014; Zhang, Wu, Wu et al., 2014; Zheng et al., 2015; Zhou, Wu, Zhang, Fu, & Hao, 2014). They vary in several factors such as the vehicle type under study, urban structure, testing conditions and technologies, and the time of study, which correspond to the emission standards in place. Focusing on vehicle emissions, number of vehicles and emission standards, some studies also provide future trends of on-road vehicle emissions in China (Hao, Liu, Zhao, Li, & Hang, 2015; Wang, Fu, & Bi, 2011; Wu et al., 2017; Zhang, Wu, Wu et al., 2014).

Reduction of GHG emissions from conventionally-fueled vehicles is the main impetus behind alternative fuel vehicles such as hydrogen and electric vehicles, as well as those running on biofuels. Development of more fuel-efficient vehicles and methods to reduce transit delay also reduce air pollution and GHG emissions. However, even if alternative fuel vehicles meet the growing mobility needs and emission reduction targets, the increased number of vehicles could still lead to increased travel time, congestion, particle pollution, and vehicle noise (not for electric vehicles). Such issues could reach a level where only changes in transportation systems could accommodate the growth in mobility demand.

2. Recent Findings on Ridesharing Potential

Ridesharing is often defined as the sharing of vehicles by commuters who share common routes and trip schedules to reduce the overall number of trips and travelled distance. In general, the shared vehicles include personal cars, vans, taxies and shuttles, and the shared routes include rides to work and common household trips. In this article, ridesharing encompasses the use of personal vehicles for common routes and schedules. Ridesharing is a potential option to increase mobility while maintaining or reducing vehicle emissions by increasing the effective use (efficiency) of existing transportation resources. There are several options to support ridesharing such as designated carpooling lanes, and web-based applications to connect drivers. Higher vehicle use corresponds to fewer circulating vehicles, increased efficiency of urban traffic, less congestion, reduced local air pollution, and lower overall GHG emissions. Several studies focused on the effectiveness of ridesharing in managing congestion. While most studies identify significant benefits, the potential for ridesharing varies significantly. Alexander and González (2015) suggest a 43% decrease in the number of vehicles in the Boston area with adoption of ridesharing among drivers. They also found that a 14% increase in the number of vehicles would occur if only non-drivers (e.g., transit riders) were to adopt ridesharing. Cici, Markopoulou, Frias-Martinez and Laoutaris (2013, 2014) showed that ridesharing could provide more than 70% reduction in the number of cars in Madrid. Bicocchi and Mamei (2014) showed that the number of trips could decline by over 40% if users within a 1-kilometer distance shared rides in Italy. Goel, Kulik and Ramamohanarao (2016) examined vehicle reductions in Melbourne when passengers are picked-up and dropped-off at predetermined stops. Their model suggested a 23–40% reduction in vehicle kilometers depending on the strategies used in selection of the stops. He, Hwang and Li (2014) found that increasing the number of riders to eight per vehicle, by using a mini van, would increase overall travel savings up to 60%. In an investigation for taxi ridesharing in New York City, Santi et al. (2014) concluded that, with waiting time not exceeding 5 minutes, ridesharing with two or three passengers could reduce total taxi trips by 50% (reaching full potential in trip reduction) and 60%, respectively. This equates to about a 40% reduction in total taxi trip length. Another investigation for taxi ridesharing in New York City (Ota, Vo, Silva, & Freire, 2015) identified 46% and 61% savings, respectively, in taxi trips if rides are shared among two and three passengers with nearby trips within 1.6 kilometers. Using the same algorithm for analysis of taxi ridesharing potential proposed by Santi et al. (2014), Tachet et al. (2017) showed that ridesharing benefits follow the same trends in San Francisco, Vienna and Singapore with total number of taxi trips reduced by 50% for San Francisco and Singapore, and by 42% for Vienna.

Conclusions drawn from past studies on the benefits of ridesharing are affected by the specific land use characteristics of the city under investigation (Kim, Rasouli, & Timmermans, 2017) and pricing preferences (Yang & Timmermans, 2017). Alexander and González (2015) expected ridesharing efficiency to decrease for cities with heterogeneous trip patterns, such as those with multiple major employment centers or with limited residential development. Conversely, simulation results of Tsao and Lin (1999) and Cici et al. (2014) showed that cities with uniform home and work locations provide little potential for ridesharing. Tachet et al. (2017) showed that the potential of ridesharing follows the same trends in New York City and three other major world cities, which differ greatly in traffic characteristics associated with population size and urban extent.

3. Factors Affecting Evaluation of Ridesharing Potential

In the analysis of ridesharing potential using driver mobility data, it is crucial to define what data is measured, how it is measured and how the data is analyzed. These parameters can greatly impact findings and are often the reason behind varied results in various studies. They are reviewed in the next two subsections.

3.1. Vehicle Trip Data Set

In order to analyze ridesharing potential to reduce the overall demand for personal vehicles, large-scale data on vehicle mobility patterns in a city is needed. This could include recorded location and time of day for all vehicles for a given time period (e.g., a day). The datasets used in ridesharing models vary depending on the following:

- **Granularity of data** (spatial and temporal). This often depends on the tools used to collect data (e.g., cellphone [Alexander & González, 2015; Cici et al., 2014], GPS systems [He, Hwang, & Li, 2014; Tachet et al., 2017; Trasarti, Pinelli, Nanni, & Giannotti, 2011], surveys [Ghoseiri, Haghani, & Hamedi, 2011] and social networking tools [Cici et al., 2014]). In general, cellphone datasets often in the form of Call Detail Records (CDRs) have less granular information in terms of user trajectories since they often record user information when users make calls or send text messages. For the purpose of big data collection on user mobility for ridesharing analysis, cellular data can be collected from network companies. Accuracy of such cellular data, often not specifically designed to indicate accurate location by using cellphone applications, is limited by the density of existing cellular towers in the area of user movements. Cellular telephone towers could in some cases cover a large area (up to several square kilometers) in rural areas resulting in less accurate data. GPS data, on the other hand, rely on satellites and provide more accurate descriptions of user movements. Collection of cellular data from a larger number of users can provide data with acceptable accuracy and comparable to GPS-collected data (Cici et al., 2014). Data from online networks are also unable to reach high granularity, as they can only be collected when users post a geotagged message in a social network.
- **Dataset size**. This corresponds to the number of recorded trips over a period of time that alternatively affects the potential of ridesharing. Santi et al. (2014) studied how the number of shareable trips in a given day varies as a function of the total number of recorded trips. In their study, the average number of daily-recorded trips in New York is around 400,000 and they showed that at approximately 100,000 trips, taxi ridesharing potential reaches its maximum theoretical value.

3.2. Data Analysis to Model Ridesharing

Once data on user mobility patterns are collected, extraction of suitable information and analysis to identify potential shared rides is a complex process consisting of several stages and dependent on several factors. Potential ridesharing opportunities are often presented as the fraction of individual trips that can be shared, sometimes called *shareability* (Tachet et al., 2017). Agatz, Erera, Savelsbergh and Wang (2012) highlighted many of the optimization challenges that arise when developing technology to support ridesharing and reviewed the relevant operations research models in this area.

3.2.1. Spatial and Temporal Constraints

Findings of user trip compatibility analyses are directly affected by the maximum allowed extra distance for each trip as a result of ridesharing and the spatial (i.e., ride potential within a certain distance) and temporal (e.g., pick up and drop off within a time frame) constraints. For example, Cici et al. (2014) found that traffic in the city of Madrid could be reduced by 59% if users are willing to share a ride with people who live and work within 1 kilometer. However, once a pick-up and drop-off delay of up to 10 minutes is placed on the model, this potential benefit drops to 24%. Santi et al. (2014) used a delay time of up to 5 minutes while Ota et al. (2015) used extra distance traveled for recognition of nearby potential rides. He et al. (2014) showed that excessive detouring (i.e., larger than 4 kilometers) reduces ridesharing efficiency to less than 5%.

3.2.2. Number of Users Allowed to Share Rides

Some studies investigate the effect of the maximum number of rides to be shared on the ridesharing potential. He et al. (2014) and Ota et al. (2015) found that as the limit on the number of shared rides increases, *shareability* potential also increases. Results of simulations by Santi et al. (2014), however, showed the number of saved taxi trips is increased from about 50% (maximum theoretical potential) with two shared rides to only about 60% with three (below the 66.7% maximum theoretical potential) suggesting that the benefits of ridesharing do not increase linearly with the number of shared rides. It must be noted that an increase in the number of allowed shared rides is expected to increase extra travel distance and number of extra stops for each trip, two parameters that are often set to limited values in the models. Increasing the number of allowed shared rides would likely be ineffective in increasing *shareability* potential if these parameters are strictly kept at relatively low values. Ota et al. (2015) found that for three shared trips, the total saving in the total distance through ridesharing is 29% on average with the average extra distance of 0.92 kilometers, while for two shared trips the saving is 18.2% with the average extra distance of 0.56 kilometers.

3.2.3. Trip Matching Algorithms: En-Route versus Origin-Destination Ridesharing

Another factor affecting the findings are the trip matching algorithms used in the analysis, and the ability of the model to capture en-route ridesharing (i.e., ride potential along trips). Studies that analyze user spatial and temporal compatibility based on trip start- and end-points are often not capable of modelling such potential and are expected to report a lower potential for ridesharing. Cici et al. (2014) performed both types of algorithms and found that ridesharing potential increases from 24% to 53% if en-route ridesharing opportunities are modeled as well. Bicocchi and Mamei (2014) also presented a methodology, based on the extraction of suitable information from mobility traces, to identify rides along the same trajectories.

3.2.4. Dynamic versus Static Ridesharing

In some models, it is assumed that trips are known in advance, which makes them suitable for carpooling applications but debatable for taxi ridesharing applications where opportunities are computed in real time. Taxi ridesharing requests arrive in real time and the algorithms used in evaluating such potentials need to run large-scale studies that explore a wide range of scenarios through parameter sweeps. This often takes considerable computation time and although many algorithms are capable of evaluating ridesharing potential among users, some are not able to evaluate such potential under the time constraints typically present in applications used for connecting users. Thus, the time constraints affect the calculated potential by the algorithms. In order to model the time-sensitivity of ridesharing potential, a time window is often used in the algorithms, outside of which ridesharing potential is not considered practical in real-time situations (Maciejewski et al., 2016; Shen et al., 2016). Therefore, potential of ridesharing is generally found to be lower in studies that account for this factor. For example, Cici et al. (2013, 2014) showed that a time window of 10–30 minutes results in 10–20% reduction in the number of cars in real-time situations if a delay time of 10 minutes and a detour distance of one kilometer are accepted by users. Without this time restriction, they show a higher ridesharing potential of up to 60%.

3.2.5. Techniques Used in Ridesharing Data Analysis

In ridesharing analysis, optimization methods substantially increase the likelihood that ridesharing matches can be found for participants, and lead to ridesharing models that generate larger overall system savings. Agatz, Erera, Savelsbergh and Wang (2011) simulate ridesharing potential (e.g., miles saved) for various optimization objectives such as rider travel time and cost.

Santi et al. (2014) proposed a graph-based approach that is capable of spotting opportunities for en-route ridesharing. The algorithm computes optimal sharing strategies for taxi trips in New York City considering two parameters: the maximum number of trips that can be shared and the minimum time to accommodate all trips.

He et al. (2014) proposed a carpooling system that generates an efficient route for dynamic ridesharing using a GPS-assisted trajectory mining scheme to identify frequent routes taken by participating riders, including private car, taxi, bus, subway and walking. The routing optimization goal is to minimize the driving distance, commute costs, detour distance, social distance and advance time to start the carpool.

Ma, Zheng and Wolfson (2013), Ota et al. (2015) and Ota, Vo, Silva and Freire (2016) proposed a framework that supports the simulation of real-time taxi ridesharing scenarios. Ma et al. (2013) split a region into grid cells such that the distance between any two locations can be computed “heuristically” as the distance between the cells containing them. This allows their system to keep shortest path computations at a minimum. Ota et al. (2015) used a shortest path indexing scheme, where they made use of cache-coherent layout to speed up shortest path queries substantially, and presented a framework that supports the simulation of real-time taxi ridesharing scenarios.

Alexander and González (2015) extracted average daily origin-destination trips from the dataset and matched spatially and temporally similar trips. They evaluated the impacts of congestion network-wide for several adoption scenarios including adoption of ridesharing by non-drivers.

3.3. Factors Affecting Adoption of Ridesharing

In the analysis of ridesharing potential, indirect factors affecting adoption of ridesharing, such as passenger safety (i.e., riding with strangers) and privacy (i.e., disclosure of home and work address) are sometimes accounted for. Some studies focused on characterizing crowd mobility and activity patterns using information from social networks (Fujisaka, Lee, & Sumiya, 2010; Noulas, Mascolo, & Frias-Martinez, 2013; Noulas, Scellato, Mascolo, & Pontil, 2011; Wakamiya, Lee, & Sumiya, 2011). Cici et al. (2014) used online social network data to apply social constraints in the analysis of the data for matching drivers (e.g., ridesharing among people who know each other). They found that if users are willing to ride with friends of friends, the potential reduction is up to 31%, but if they are willing to ride only with people they know, the potential of ridesharing becomes negligible. Fixed pick up/drop off locations equipped with video surveillance could improve riders’ safety and protect their privacy (Goel et al., 2016). Such fixed locations can be selected to maximize vehicle occupancy.

4. Objective: Estimation of Emission Reductions as a Result of Ridesharing

In most previous studies, ridesharing potential in improving congestion is investigated. Some studies focused on presenting algorithms that are suitable for real-time ridesharing requests, often used for connecting taxi users. While the studies present the results in the form of ridesharing efficiency or the number of trips saved, they do not provide an approximation of reduced pollutant and/or GHG emissions resulting from the trip savings. Ota et al. (2015) analyzed the savings in CO_2 emissions, but they do not explicitly present their results on CO_2 emissions in their article. In addition, studies that focus on the emissions of vehicles in China often focus on how fuel and engine improvements that comply with the emission standards result in emission reductions. They do not focus on indirect strategies such as increasing vehicle occupancy averages that can reduce overall emissions. In the current study, the potential of ridesharing to reduce pollutant and GHG emissions is investigated. Trip GPS data of approximately 9,000 privately-owned vehicles in Changsha, China, is used. Ridesharing potential is identified based on trip origin and destination. The savings on trip distance as a result of ridesharing is used to provide estimates of pollutant and greenhouse gas emission reductions. The findings suggest the potential of ridesharing to improve local air quality and mitigate GHG emissions.

5. Methods

This section introduces a proposed data-driven model that enables the analysis of historical location data to investigate the potential of ridesharing. There are several challenges related to this research, including removal of outliers, noise and false data, investigation of the reliability of data, detection of misrepresented information in terms of location, feature selection, and clustering the data which significantly affect the findings. Figure 1 illustrates the data flow diagram to analyze ridesharing potential that consists of three steps of data processing including pre-processing, similarity detection and ridesharing recommendations.

In this study, the vehicles' geographical locations (latitude and longitude) were collected using GPS monitoring systems installed in 8,900 privately-owned vehicles in Changsha, China (population of 7 million). The historical data is processed to determine possible similar rides that could be shared. The potential number of saved kilometers by adopting ridesharing is calculated.

It should be noted that ridesharing in the current analysis is short-distance, static (see Section 3.2.4) and is on a daily basis. It is also assumed that wherever matching trips exist, one car corresponding to the longest trip is selected as the one that provides a ride to others, and is the one setting the origin and destination of the shared trip. Passengers of the cars corresponding to the other trips (i.e., riders) are expected to walk the last part of their trip (also called the last mile) from the driver's destination to theirs.

5.1. Pre-Processing

5.1.1. Trajectory Representation and Location History Modeling

As depicted in Figure 1, spatial-temporal trajectories are first built from the GPS logs. The data is retrieved from the database for each vehicle and transformed to a series of chronologically ordered points for example, $P_1 \rightarrow P_2 \rightarrow P_3 \rightarrow \ldots \rightarrow P_n$. Each trajectory point consists of timestamp, geospatial coordinates (latitude, longitude) and the speed of the vehicle.

Data pre-processing is a crucial step as data collection is often loosely controlled, resulting in outliers, noise, and missing information. Thus, to reduce the complex-

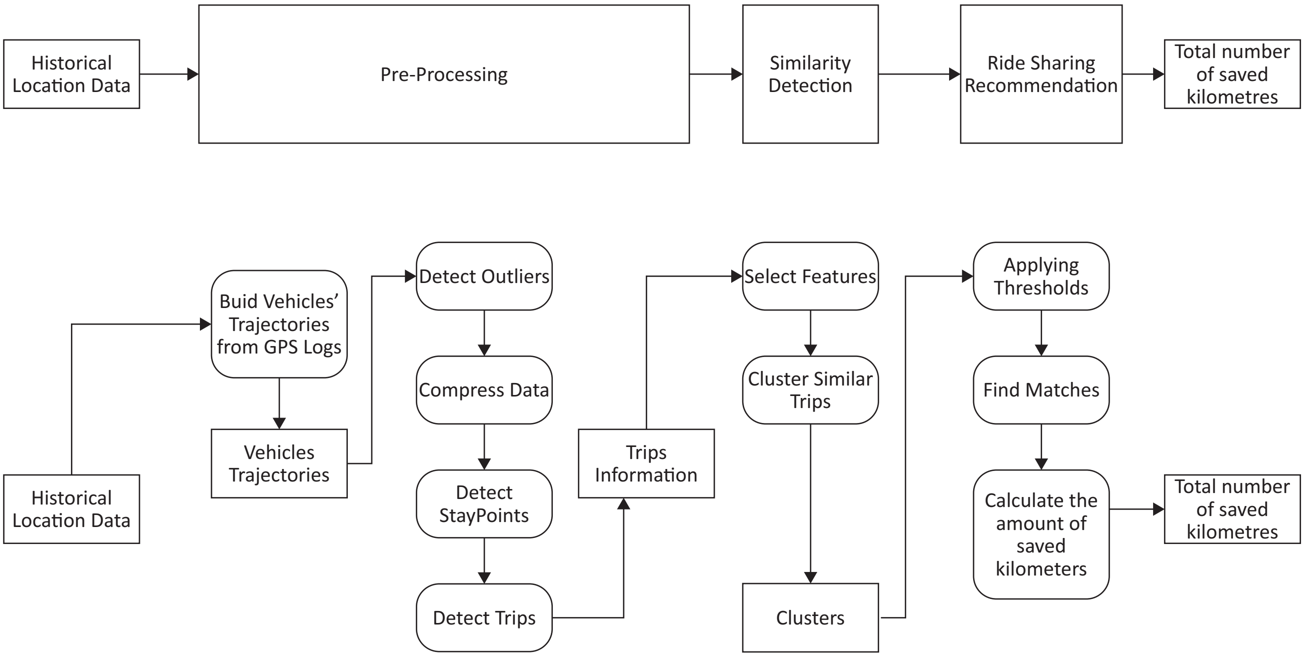

Figure 1. Data flow diagram for ridesharing.

ity of data analysis and program execution time, the following data pre-processing and representation steps were applied.

5.1.2. Noise Filtering and Outlier Detection

The first step in data pre-processing that looks for abnormalities in trajectories is noise filtering and outlier detection. Outliers in trajectories can be a point or series of points that are significantly different from other points. For instance, an outlier can be a point that is far from other points and out of vehicle possible reach within regulated speed and time. An outlier can also be a point observation that does not conform to the expected pattern. In this paper, we used mean filter (Huang, Yang, & Tang, 1979) to detect the noise and outlier. For point P_z, in a vehicle's trajectories, a true value is the mean of the position of P_z and the $n-1$ predecessor, thus, the mean filter can be a sliding window covering the n adjacent values of P_z:

$$\frac{1}{n}\sum_{i=(z-n+1)}^{z} P_i$$

where n is the size of sliding window for the mean filter.

5.1.3. Compression

While vehicle locations can be constantly sampled and communicated, a high rate of sampling can result in excessive communication overhead, computing and data storage. It is also important to consider that when a vehicle is waiting at a traffic light, or delayed in congestion, its location does not change for a while but sampled continuously. To decrease the amount of data and improve the performance of data processing, the points from trajectories for which there is no updated information are removed.

5.1.4. Stay Point Detection

An important part of the analysis is to detect stay points because they can be used in trajectory segmentation and trip detection. Stay points denote the locations where vehicles stay for more than 5 minutes, such as parking lots. There are two different types of stay point: First, single point location where a vehicle remains stationary, and second, when a vehicle location is updated but there is no notable change on a vehicle location. In this study, both types of stay point are detected.

5.1.5. Trip Detection

To group similar trips, one needs first to divide a trajectory into different trips. Segmenting trajectories to trips helps to reduce computation cost, delve deeper into vehicle trajectories and find more potential ridesharing options. In this paper, trips are detected based on time interval and stay points. For example, if the time interval between two consecutive points in a vehicle trajectory is larger than a defined threshold, the vehicle trajectory can be divided to two trips. Also, stay points can divide a trajectory into two different segments or trips.

5.2. Similarity Detection

The main purpose of our analysis is to detect the similar rides and mark them for potential ridesharing. In this step, clustering detects similar trips and groups them together.

5.2.1. Feature Selection

As different trips contain different properties such as length, number of points, and sampling rate, it is difficult to use trip properties for clustering. To solve this issue, one can select useful features from each trip and present them in a uniform way. In this paper, the start time, end time, origin, destination and length of each trip are used to describe the features for each trip and are represented as a vector.

5.2.2. Clustering

Clustering in this analysis is the process of grouping similar trips. The trips inside a group are more similar than other trips that are placed in other groups or clusters. The distance between the trips is measured by distance between vectors. Clustering tries to minimize the distance between the trips inside of each cluster and maximize the distance between trips outside of each cluster.

One of the most commonly used algorithms for clustering is the k-means (Hartigan & Wong, 1979). *k*-means is an iterative clustering algorithm that partitions *n* observations into a number of clusters (*k*) that is selected before the algorithm starts. In this study, *K*-means is used for grouping similar trips. *K*-means chooses *k* initial cluster centers randomly and calculates the distance of the centroid in each cluster to all the trips and then assigns each trip to the group with closest centroid. After that, *K*-means calculates the average distance between trips inside of each cluster and the cluster centroid to find the new centroid. *K*-means repeats these steps until the cluster members do not change.

For measuring the similarity between trips and their centroids, we employed multiple similarity functions such as Euclidean, Cosine, City block and Correlation (Deza & Deza, 2009). For each of these functions, we calculated the distance based on the following equations:

$$\text{Euclidean: } d(x,c) = \sqrt{\sum_{i=1}^{p}(x_i - c_i)^2}$$

$$\text{City block: } d(x,c) = \sum_{i=1}^{p}|x_i - c_i|$$

$$\text{Cosine: } d(x,c) = 1 - \frac{xc'}{\sqrt{(xx')(cc')}}$$

$$\text{Correlation: } d(x,c) = 1 - \frac{(x-\bar{x})(c-\bar{c})'}{\sqrt{(x-\bar{x})(x-\bar{x})'}\sqrt{(c-\bar{c})(c-\bar{c})'}}$$

where $\bar{x} = \frac{1}{p}\left(\sum_{j=1}^{p} x_j\right)\bar{1}_p$ and $\bar{c} = \frac{1}{p}\left(\sum_{j=1}^{p} c_j\right)\bar{1}_p$

where p is the dimension, x is an observation or feature vector for a trip, c is a centroid and $\bar{1}_p$ is a row vector of p ones.

5.3. Ridesharing Recommendation

Clustering partitions similar trips into groups but it does not guarantee that all the trips inside each group have the potential for ridesharing. There are still limitations for ridesharing such as the maximum distance between the trip start and end points, the maximum user schedule time, the maximum number of passengers who can share the ride, or the minimum length for which two users prefer to travel together. In this step, such thresholds are considered for each cluster and the potential trips that could be shared are estimated.

6. Experimental Analysis

In this section, the performance of our approach is demonstrated using GPS location records of 8,900 privately-owned vehicles in Changsha. In the experiments, the effect of different similarity functions along with different number of clusters on the clustering algorithm are examined to find the best option for ridesharing. We also examined the effect of maximum schedule time and maximum distance between the trip start and end points. The results show that Euclidian similarity function with 11,000 clusters achieves the best performance and there is no notable change on the total saved kilometers if we increase the maximum schedule time to more than one hour and the maximum distance between the trip start points and endpoints to more than 6 kilometers.

6.1. Experimental Setup

The historical data of every vehicle was sampled every 10 minutes and stored in a database. Thus, the historical dataset that we studied was also sampled every 10 minutes totaling 65,940,000 records spanning 89 days from February to April 2013. In an ideal situation, each vehicle creates 144 records per day resulting in 114,062,400 for 8,900 vehicles for 89 days but our monitoring system did not collect the data from vehicles that remained stationary for more than 12 hours. Also, there is typically data loss which can be attributed to a variety of reasons. For example, monitoring data was wirelessly communicated to the monitoring platform using cellular GPRS networks which is error-prone due to the nature of the wireless channel that introduces data loss, delay, and retransmissions.

The experiments ran on a server with Intel 6 cores Xeon E5649 2.53GHz processor, 32 GB RAM and Windows server 2016 operating system running MATLAB R2016b. MATLAB is used as the programming environment for the experiments. We also used MATLAB parallel computing toolbox to get maximum benefit from multiple cores inside the server processor. The toolbox enabled the use of the full power of multicores by executing our program on multiple threads.

6.2. Ridesharing in 24 Hours: Case Studies

To demonstrate the performance of the approach, the first day (24 hours) of the dataset which contains 1,080,224 records was selected. This is a weekday including travel typical of all weekdays travels. The total traveled distance on this day is 201,890 kilometers, and the total number of detected trips is 20,018 resulting in an average trip length of 10.53 kilometers. Figure 2 shows the total hourly travel distance driven by the vehicles for 24 hours on the first day of the dataset, and Figure 3 shows the trip start points for 24 hours on an actual map. When rides are shared, we assumed that the maximum capacity of each vehicle, including the driver of the vehicle, is 4 passengers. In addition, we assumed that sharing rides that are shorter than 2 kilometers result in excessive detouring and provide negligible benefits in terms of reductions in overall trip kilometers and therefore, trip data corresponding to such trips were excluded from the experiment.

6.2.1. Effect of the Similarity Function on Ridesharing

6.2.1.1. Case Study 1

In the first case study, the effect of different similarity functions and maximum schedule time on ridesharing potential (indicated in this article as the kilometers and the number of trips that are reduced) were evaluated. Table 1 shows the values assigned for the simulation setup parameters for the first case study. We assumed that the number of clusters is constant and equal to 8,000 clusters. To match trips with ridesharing potential, the maximum time that passengers can wait to get a ride (referred to schedule time in this article) and the maximum allowable distance between trip origins and destinations (also referred to as trip distance in this article) are set. In this case study, the maximum schedule time is varied between 5 and 180 minutes and the maximum distance between trips is set to 2 kilometers. It is found that the Euclidean and City block similarity functions result in the highest values of total saved kilometers (Figure 4a) and total number of saved trips (Figure 4b) if the maximum schedule time is less than an hour. If the maximum schedule time is higher than 60 minutes, the City block similarity function indicates higher values in total

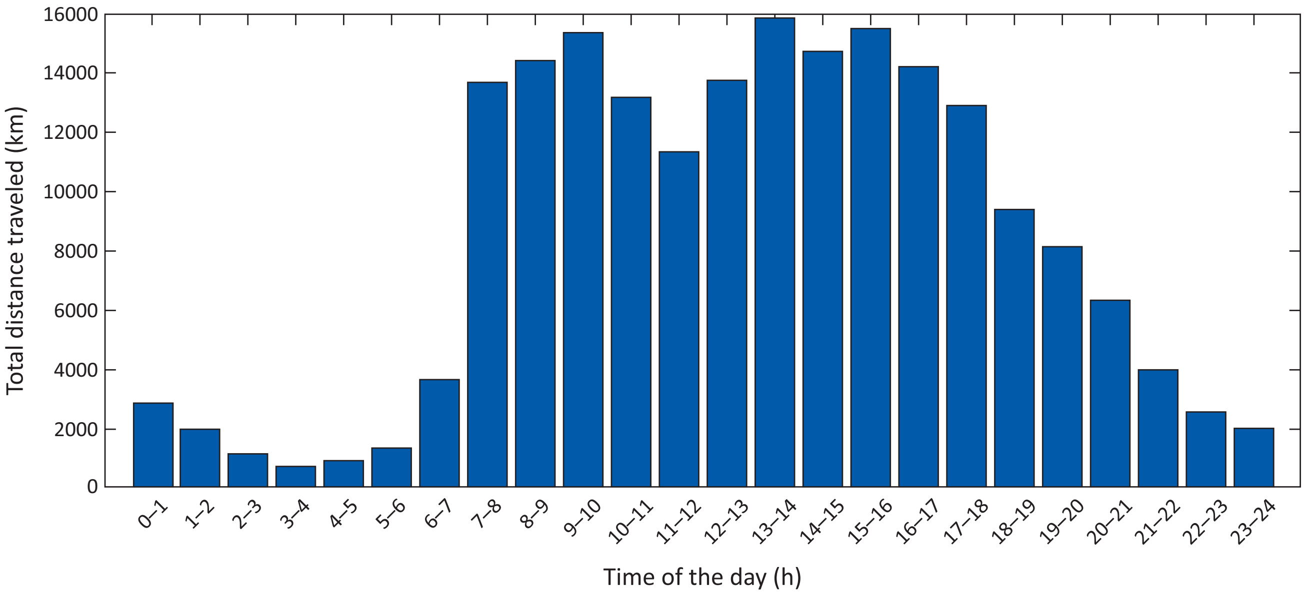

Figure 2. Total hourly distance driven by vehicles for 24 hours.

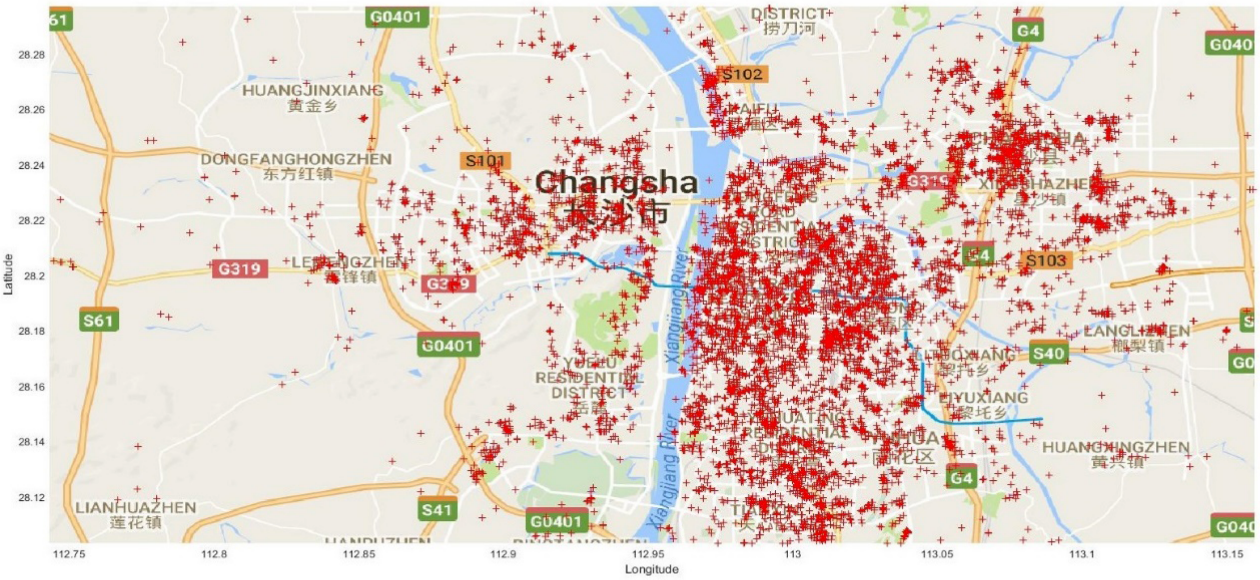

Figure 3. Trips start points (red dots) for 24 hours.

Table 1. Simulation set up parameters (study 1).

Description	Value
Similarity Function	Variable
Maximum distance between trips (Kilometers)	2
Number of clusters	8000
Maximum schedule time (Minutes)	5–180
Total trip length (Kilometers)	210,890
Total number of trips	20,018

saved kilometers and saved number of trips than other functions. Euclidean and City block have better results in terms of saved kilometers because these two similarity functions act better on the data that can be represented as points in a Euclidean space. The cosine similarity measures the angle between two vectors and while it is a suitable candidate for multi-feature vectors, it did not perform well for the small number of features' vectors. The correlation similarity function is also only suitable for high-dimensional data which is not the case in this study.

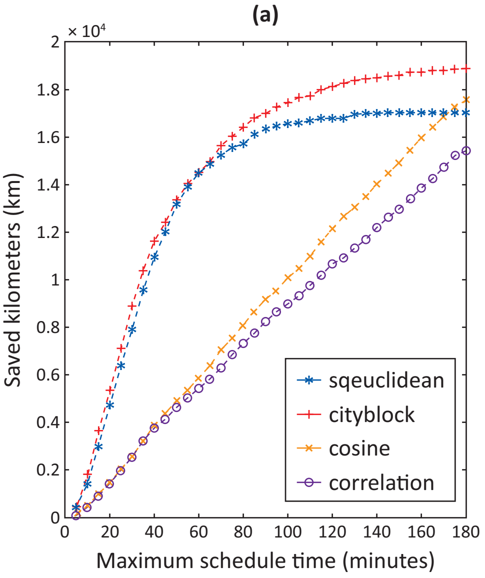

Figure 4. Effect of similarity function and maximum schedule time on (a) saved kilometers (b) number of saved trips.

6.2.1.2. Case Study 2

In this case study, the effect of the similarity function and the maximum distance between trips on ridesharing potential are evaluated. Table 2 shows the values assigned for the set-up parameters for the second case study. We assumed that the number of clusters is a constant and equal to 8,000 clusters. The maximum schedule time is set to 40 minutes, and the maximum distance between trips is a variable between 1 and 20 kilometers. It is found that the Euclidean and city block similarity functions result in higher values of total saved kilometers (Figure 5a) and number of saved trips (Figure 5b) compared to the cosine and correlation functions. As one can see in Fig-

Table 2. Simulation set up parameters (case study 2).

Description	Value
Similarity Function	Variable
Maximum distance between trips (Kilometers)	1–20
Number of clusters	8,000
Maximum schedule time (Minutes)	40
Total trip length (Kilometers)	210,890
Total number of trips	20,018

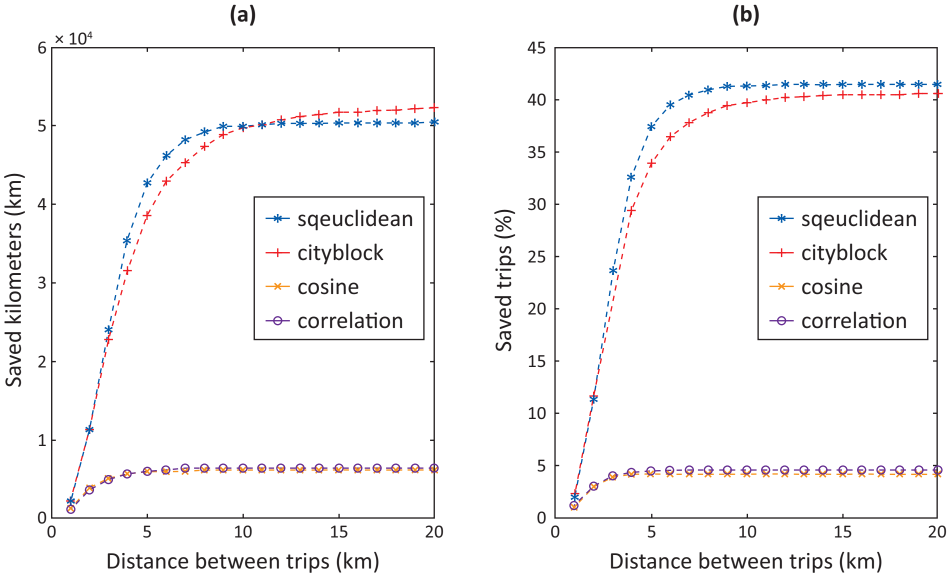

Figure 5. Effect of similarity function and distance between trips on (a) saved kilometers (b) number of saved trips.

ure 5, there is no improvement in ridesharing potential if the distance between the trips is more than 6 kilometers. The reason behind this is the decrease in the similarity among trips when the distance among them is increased. Ultimately, when the distance is more than 6 kilometers, there is no similar trip available for matching inside each cluster.

6.2.1.3. Case Study 3

In the third case study, the effect of the similarity function and the number of clusters on ridesharing potential was investigated. Table 3 shows the values assigned for the set-up parameters for the third case study. We assumed that the number of clusters is a variable between 1,000 to 15,000. The maximum schedule time is kept to 40 minutes, and the maximum distance between trips is kept to 3 kilometers. The highest values of saved kilometres and total number of saved trips are achieved with the Euclidean similarity function when the number of clusters is approximately 11,000 (Figure 6). As Figure 6 depicts, increasing the number of clusters to more than 11,000 does not increase the total number of saved kilometres. This can be explained by the decrease in the number of similar trips inside of each cluster as the number of clusters are increased.

6.2.2. Case Study 4: Effect of the Number of Clusters and Schedule Time on Ridesharing

In this case study, we looked at the effect of changing the number of clusters and schedule time on ridesharing potential. Table 4 shows the values assigned for the set-up parameters for the forth case study. We assumed that the number of clusters is a variable between 1,000 and 15,000, the maximum schedule time is a variable between 5 and 180 minutes, and the maximum distance between trips is a constant, equal to 3 kilometers. The largest reduction in traveled kilometers is achieved with 11,000 clusters if the maximum schedule time is less than an hour. (Figure 7).

6.2.3. Case Study 5: Effect of Maximum Trip Distance and Schedule Time on Ridesharing

In Case study 5, the effect of trip distance and schedule time on ridesharing potential is investigated. Table 5, shows the set-up parameters for this case. As we determined in the previous case studies, the highest values of saved kilometers are achieved using the Euclidean similarity function with 11,000 clusters. In this case study, we kept the number of clusters at 11,000 and used Euclidean distance for the similarity function. The results show that

Table 3. Simulation set up parameters (case study 3)

Description	Value
Similarity Function	Variable
Maximum distance between trips (Kilometers)	3
Number of clusters	1000–15,000
Maximum schedule time (Minutes)	40
Total trip length (Kilometers)	210,890
Total number of trips	20,018

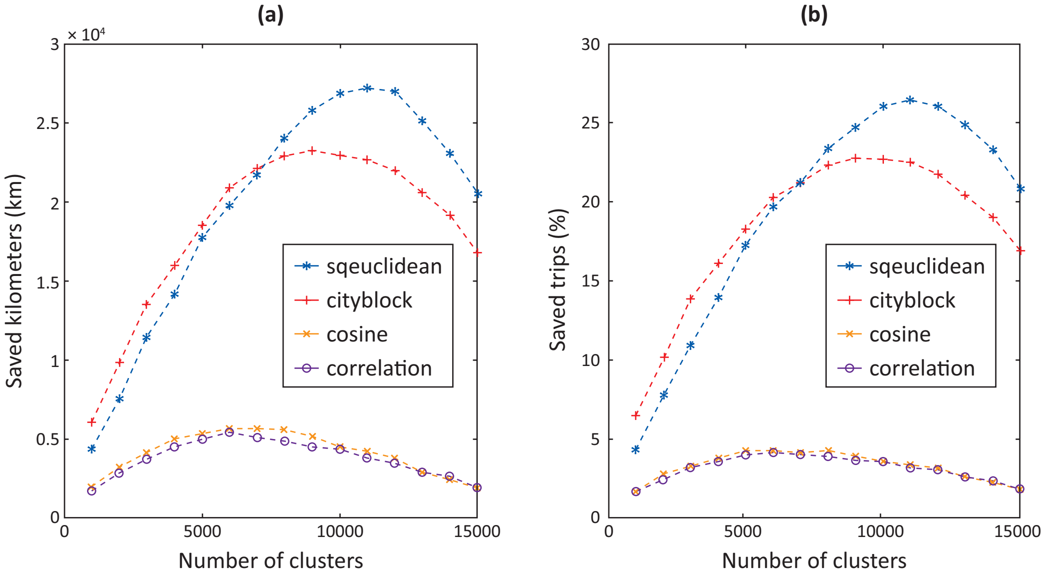

Figure 6. Effect of similarity function and number of clusters on (a) saved kilometers (b) number of saved trips.

Table 4. Simulation set up parameters (case study 4).

Description	Value
Similarity Function	Euclidean
Maximum distance between trips (Kilometers)	3
Number of clusters	1,000–15,000
Maximum schedule time (Minutes)	5–180
Total trip length (Kilometers)	210,890
Total number of trips	20,018

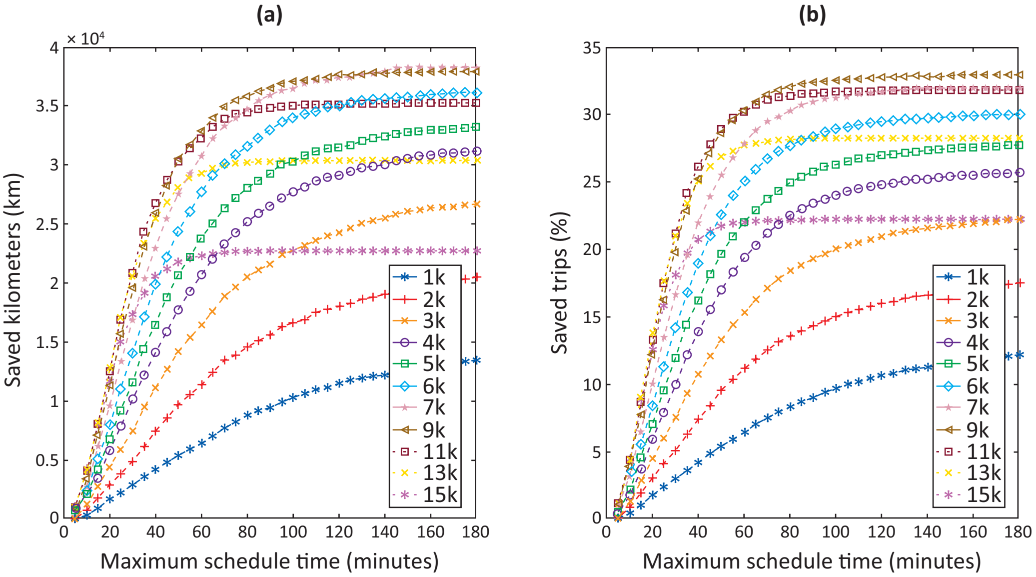

Figure 7. Effect of number of clusters and maximum schedule time on (a) saved kilometers (b) number of saved trips.

Table 5. Simulation set up parameters (case study 5).

Description	Value
Similarity Function	Euclidean
Maximum distance between trips (Kilometers)	1–10
Number of clusters	11,000
Maximum schedule time (Minutes)	5–180
Total trip length (Kilometers)	210,890
Total number of trips	20,018

we can save more than 15% on total travel distance (Figure 8a) and more than 30% on the number of trips (Figure 8b) if the maximum distance between trips is 3 kilometers and the maximum schedule time is 45 minutes. It is observed that if we increase the maximum schedule time to more than 60 minutes, there is no significant change in the number of saved kilometers and therefore, the maximum time lag between the trips inside any cluster is 60 minutes. Also, by increasing the maximum distance between the trips to more than 6 kilometers there is no change in the number of total saved kilometers.

7. Estimation of GHG and Pollutant Vehicle Emissions

In order to estimate the emission reductions resulting from the estimated saved kilometers in Section 6, emission factors are often used. However, the reported emission factors of vehicles tested under various emission standards in China vary significantly. For example, carbon monoxide (CO), non-methane hydrocarbon (NMHC) and nitrogen oxides (NO_x) emission factors of pre-Euro 1 gasoline vehicles are 15, 40 and 8 times those of their Euro 3 counterparts, respectively (Huo et al., 2012). Due to these broad variations, there is a high level of uncertainty in emission factors used in this study. Therefore, this study does not attempt to provide accurate figures for emission reductions, but rather an order of magnitude for the emission reductions that could result by adoption of ridesharing. Focusing on vehicle emissions, the number of vehicles and emission standards, Wang et al. (2011) project future trends in HC, CO, NO_x, particulate matter (PM10) and carbon dioxide (CO_2) emissions of personal vehicles based on three scenarios. The emission factors projected for light-duty passenger ve-

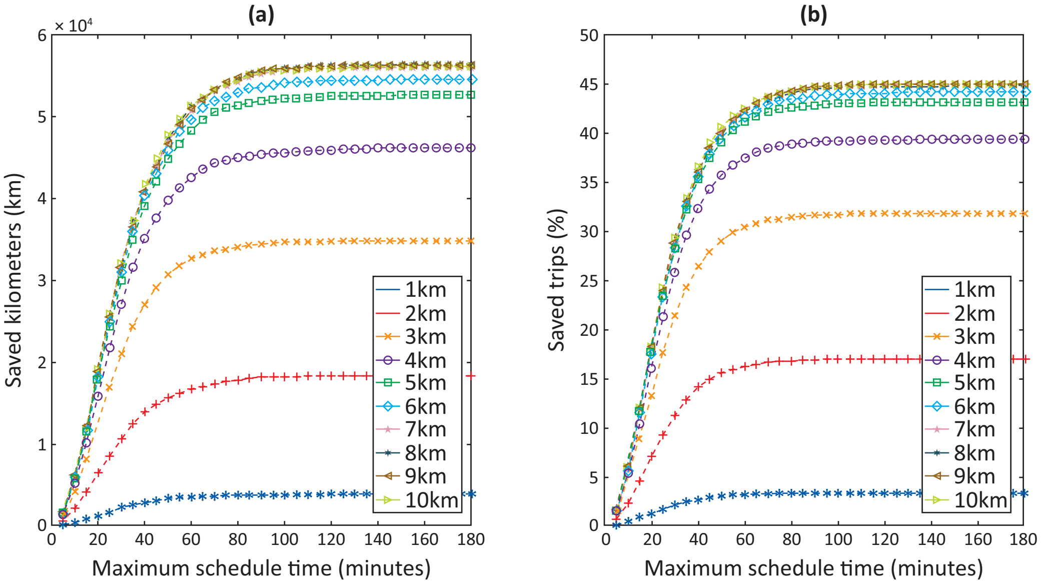

Figure 8. Effect of trip distance and maximum schedule time on (a) saved kilometers (b) number of saved trips.

hicles in 2015 and 2020 under the "recent policy" scenario is used in this study to evaluate the reduction in emissions that could result from ridesharing. In this scenario, it is assumed that PreEuro 1 to Euro 5 emission standards scheduled in stages from 2000 to 2013 are fully implemented.

Using the results presented in Section 6, potential pollutant and GHG emission reductions for a typical day resulting from adoption of ridesharing among the group of vehicles that are investigated are presented in Table 6. The emission reductions are estimated for 2015 based on available emission standards, and projections of the emission standards and their impact on vehicle emissions by 2020 are also used to evaluate the impact of ridesharing under lower emission factors. Assuming the number of vehicle kilometers taken during a typical day in 2020 remains the same, it is observed that ridesharing adoption provides lower pollutant and GHG emission reductions in 2020, but still considerable enough to make it a practical transportation strategy in the future as well. The reduction in the number of kilometers traveled when rides between drivers, within 2 kilometers and 40 minutes of departure location and time, respectively, are shared (see Section 6.2.3.1 and Table 5 for more details), results in approximately 3.1 and 0.0028 tons of CO_2 and NO_x emission reductions, respectively. This is equivalent to approximately 4.0 tons CO_2 emission reductions [Global warming potential (GWP) of 100 years]. The emission reductions provided in Table 6 provide estimates for the order of magnitude of emission reductions that can be achieved through adoption of ridesharing. A more accurate estimation of kilometers saved using ridesharing and its corresponding emission reduction is dependent upon several additional factors. However, such rough estimations are useful in providing guidance to regulators and policy development for future planning.

Due to the limited size of the data set, and the dependency of ridesharing potential to the number of drivers, estimated emission reductions are a lower bound to the potential benefit of an overall rideshare system in Changsha, China. Although the results of the current analysis are specific to current mobility patterns in Changsha, they can be used qualitatively to guide the deployment and policy development regarding ridesharing in other cities.

8. Conclusions

Adoption of ridesharing among passenger vehicles in Changsha, China, as a potential strategy to reduce vehicle pollutants and GHG emissions is investigated. Historical GPS data of approximately 8,900 privately-owned vehicles in Changsha, China, are collected and is used in an algorithm that is developed to match riders with close temporal and spatial origin and destinations. The developed algorithm is capable of estimating kilometers that

Table 6. Average pollutant and GHG emissions projected for the vehicles in the study in 2015 and 2020.

	Pollutant and GHG emissions				
Projection year	**CO_2 (tons)**	**HC (kg)**	**CO (kg)**	**NO_x (kg)**	**PM_{10} (kg)**
2015	3.14	2.80	24.8	2.80	0.280
2020	3.00	1.68	15.7	1.26	0.252

are reduced among users if ridesharing is adopted. The resulting reductions in vehicle pollutant and GHG emissions are estimated using average projected emissions factors for China.

The results show that the potential of ridesharing to reduce total traveled distance and emissions varies significantly by the users' tolerance towards changes to their original trip route and departure time. For example, the potential of ridesharing in reducing vehicle emissions increases by 94% if riders are willing to walk to drivers within 3 kilometers instead of 2 kilometers to get a ride. Assuming users are able to walk to the drivers, this could translate to an addition of 10–15 minutes to their trip time. In some cases, this delay could be compensated by a reduction in vehicle trip time (e.g., availability of high-occupancy vehicle lanes).

As shown in previous studies, the size of the data set can affect the ridesharing potential among users. Therefore, the results of the current study are dependent on the size of the data set used to identify potential ridesharing opportunities among users. A larger data set (i.e., more participants) would match more riders with ridesharing. As a result, the estimated traveled distance reduction and, associated emission reductions from ridesharing adoption in Changsha, China, are expected to be higher with a larger pool of participants.

While the quantitative results of this analysis are specific to the population under study, they provide useful insights on the potential of ridesharing to improve air quality and reduce emissions associated with climate change. Changsha, China, is one of several cities around the world that uses personal vehicles as a reliable mode of transportation. The methods used in this study to evaluate ridesharing potential in reduction of traveled kilometers in Changsha and reduction in pollutant and GHG emissions can be used in future similar studies on other cities that rely partially or fully on personal vehicle transportation. Analysis of current transportation demand and projection of future trends are key tasks in planning for sustainable transportation modes such as ridesharing that are potentially able to meet future demands.

Within the study area, ridesharing has the potential to reduce total kilometers driven (210,890 kilometers) by about 24% (51,087 kilometers) and vehicle trips (20,018 trips) by approximately 40% (8480). This maximum potential assumes a maximum distance between trips less than 10 kilometers, and schedule-time less than 60 minutes (Figures 8a and 8b). If a more conservative maximum distance of 2 kilometers between trips and schedule time less than 40 minutes is selected, total distance traveled reduces by 7% and total number of trips by 14%. This translates to equivalent of approximately 4.0 tons CO_2 emission reductions daily.

It must be noted that although findings of this study illustrate the potential of ridesharing in reducing pollutants and GHG emissions, its adoption still faces challenges such as passenger safety, privacy and liability for its adoption by users. Furthermore, the success of web-based applications in connecting potential shared rides are dependent on the number of users. In terms of regulations, they compete with existing regulated taxi companies. Such limitations need to be further analyzed and solutions are needed to overcome these challenges.

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Conflict of Interests

The authors declare no conflict of interests.

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