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Emerging types of mobility services and vehicle technologies, employed ICTs and implication for transport planning and policy

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Abstract

Along with technological developments in information and communication technologies, new mobility services such as online ticketing and car-sharing, and new vehicular technologies such as connected cars and self-driving cars are emerging. However, a holistic perspective, which is essential for strategic and long-term policy-making, has been seldom available, and from such wider perspective, it is not always fully understood what kind of mobility services and technologies are or will be available, and which service or technology depends on what types of information and communication technologies. It is important to understand this because it forms a basis for long-term transport planning and policy-making at local, regional and national levels. In order to fill this gap, we carried out an extensive review of emerging mobility services and vehicular technologies, and we carried out dependency and timeline analyses among them. The key findings are that various ICTs deployed for “new” mobility services were made available already in the 1990s, while employment for mobility services takes between approximately 10 and 20 years. When autonomous vehicles with higher level of driving automation are available, various vehicle and ride sharing services, mobile journey planners and ticketing, and integrating platform like MaaS are posited to serve as a basis for integrated platform to make it possible to use in a shared manner. In this future context, long-term and strategic transport planning and policy-making has to be adapted as road infrastructure and parking regulations will have to be optimized for reduced vehicle stocks and vehicular traffic.

Keywords: shared mobility; mobile phone; vehicular technologies; ICTs; timeline analysis;

1. Introduction

Transport infrastructure and services in mechanized forms, which still play important roles in everyday mobility, had been developed by the last century. For example, the first bicycle was developed in the 19th century and has been in use since then. The railway was first developed in England in the 19th century and become widespread throughout the world. Automobiles with internal combustion engine came into the market in the middle of the 20th century, and became widespread in the postwar period in many of the industrialized countries.

Based on these classical types of vehicles and infrastructures, new types of mobility services and vehicular technologies started to appear since the 1990s. Technologically driven, electrification of automobiles has seen a great advancement in the last decades with helps from technologies related to batteries and motors. Hybrid vehicles, plug-in hybrid vehicles, and electric vehicles (EVs) are all brought into the market in the last two decades. As latest and ongoing technological developments, penetration of connected cars and self-driving automobiles, also referred to as autonomous vehicles, is foreseen to be available in the market in the near future.

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On the other hand, backed up with advancements of information and communication technologies (ICTs), particularly with the technologies associated with mobile devices connected to the Internet such as smartphones and onboard computers, various vehicle sharing services such as car-sharing (car-club) and bike-sharing have seen rapid advancements in the last decade. Sharing of rides is also made popular, and new types of services such as ride-sourcing, which connects drivers and passengers on apps, have become available widely in the world. Public transport has also been benefited from them, with ticketing on mobile apps becoming rapidly and widely available. As the latest development, concept of MaaS – Mobility as a Service – is getting popularity.

Along with these technological developments, various discussions about these new types of services have been made, while many of them focuses on one of them or on a few at most, and a holistic perspective is seldom available. This is especially the case of the period since around 2010, when various new types of mobility services emerged along with the diffusion of smartphones. On the other hand, to make strategic decisions and plans for mobility at local, regional and national scale with long-term perspectives, such an overview of the entire landscape of "new" types of services and their future outlook are essential as these new mobility services as well as new vehicular technologies will or may form a basis for mobility of passengers as well as goods in the future.

To fill this gap, in this paper, we carried out an extensive review of such emerging vehicular technologies and mobility services which have appeared in the last two decades or that are foreseen in the next decades. Furthermore, to gain a holistic outlook, we carried out a dependency analysis and timeline analysis to relate key ICTs becoming available and these emerging vehicular technologies and services for mobility. Implications for long-term and strategic transport planning and policy-making are drawn based on these.

This paper is structured as follows. In Sections 2 and 3, we present our extensive review of various types of emerging types of shared services. In Section 4, a review of various app-based services is presented. In Section 5, we review various new vehicular technologies including automated and autonomous driving. Based on these, in Section 6, an analysis of technological dependency of these technologies and various key ICTs as well as a timeline analysis of such dependencies are presented, and implications from these for long-term transport policy and planning are discussed. We conclude this paper in Section 7.

Of note, terminology for various emerging types of services differs from country to country, even among English-speaking countries. In this paper we use internationally-used terminologies: for example, what we refer to as "car-sharing" is what is called "car clubs" in the United Kingdom, while what we refer to as "ride-sharing" and "car-pooling" is what is called "car-sharing" in the UK.

2. Vehicle sharing

2.1. Introduction

In general, actions of sharing an object are categorized into two types. One is time-division sharing, with which one object is used by one person at a time, and then it is used by another person at another time. For example, *shared bathrooms, kitchen, living room, etc.* in accommodations, *shared computer* e.g. in universities' computer rooms, etc. are a few examples among many that fall in this category. Many of rental services fall in this category, too, such as rental videos/DVDs, hotel rooms, rented apartment, and so on, although these are not called as sharing. The other type of sharing is a simultaneous use of one object that can accommodate or can be used by several persons. *Shared directories* on file servers, *shared rooms* in student dormitories and youth hostels, *shared office*, etc. are a few examples of this type. In a larger scale, public facilities e.g. swimming pools, gyms, etc., public transport, etc. have the same characters although they are not called shared service.

In this way, shared mobility is categorized into two main types. The first type refers to what is called *car-sharing* internationally: with this, vehicles are shared by different users by time. A shared unit in this case is a vehicle. The second type is *sharing of rides*, with which a person rides in a vehicle of another person as a passenger. In this case, a shared unit is a trip, or even a part of a trip. In the following sections, we review vehicle sharing of automobiles, bicycles and motorbikes/scooters. In Section 3, we review sharing of rides.

2.2. Car-sharing

2.2.1. Station-based systems

Renting a car in a form of time-division rental is not a new idea, and it appeared at the time when automobile started to penetrate into the market: first documented car rental services appeared already in 1904 in the United States, and in 1912 in Germany. These are rented at staffed stations on one-time basis, as is carried out today at many of rent-a-car stations, and rented for hours or days, which is longer compared to car-sharing schemes of today. (Sixt SE, n.d., Staff of Automotive Fleet, 1962)

Modern car-sharing refers to a type of time-division car-rental system which is characterized by short-term rental by minutes or hour, fully computerized self-service reservation, pick-up and return, automated payment system, and membership requirements for its user. The station-based type offers round-trip rentals with permanent parking spots dedicated for it, often located at important nodes such as public transport stops or in neighborhoods. The reservation was made via call centers in the initial phase, while it is typically made on the Internet and smartphones today.

There have been many attempts, which often failed, since the 1970s in European countries. Making use of modern technology, with some experiences from failure, some successful models of this type of car-sharing appeared in the late 1980s, such as *Mobility Carsharing* in Switzerland, and *Stadtauto* in Germany. They became slowly but continuously widespread in the 1990s in Switzerland and Germany respectively. In parallel, car-sharing became popular in North America since the 1990s, based on a lot of experimental initiatives at universities in California. Later, commercialization of car-sharing took place, and this type of car-sharing got widespread into other developed countries. (See e.g. Jorge and Correia, 2013, Becker, et al., 2017)

Nowadays, car-sharing service operators are typically organized as cooperatives or private firms offering fleet, on-board computer systems, backend system for reservation, payment and fleet management, back office, common branding and advertisement, and so on. The operator is usually the owner of the shared cars.

2.2.2. Free-floating systems

Free-floating car-sharing is a variation of car-sharing that became widespread since c.a. 2010. It operates without any fixed stations, while shared cars are scattered throughout its service area. Some of the free-floating systems offer an "exclave" located at important nodes such as an airport. The reservation can be made at last minutes via designated smartphone apps or on the Internet. Various obstacles of fixed-station car-sharing is eased with this system, as the users are allowed to make one-way trips with different start and end points within its city-wide service areas, and reservation does not have to be made in advance, enabling short-notice and spontaneous use of shared automobile. Companies pioneering in this such as *car2go* and *Drive Now* are commercial firms initiated by automobile manufacturers, and services in early-implemented cities such as Amsterdam, Berlin, Dusseldorf, Cologne, Munich, Vancouver and Vienna were all commenced in 2011, following public tests taking places in the previous years. (See e.g. Becker, et al., 2017, BMW Group, 2018, car2go Group GmbH, 2017)

The system makes use of advanced ICTs enabling short-notice reservation with real-time location of fleets: it combines locations of available automobiles obtained from GPS, transmitted via mobile data network, and displayed on an online digital map. The user can reserve a vehicle in a near proximity, making use of geo-location information obtained from his or her smartphone.

2.2.3. Peer-to-peer car-sharing

This is characterized by a short-term rental of privately-owned vehicles. The fleet consists of a number of privately-owned vehicles instead of vehicles owned by car-sharing operators. A number of online platforms are available since around 2010, most of which targeting particular regions. It is provided as online marketplace, often with extra insurance for renting privately-owned automobiles organized by the marketplace organizer, and transaction of payments is also offered on the online marketplace. This type of car-sharing is contextualized as a form of sharing economy comparable to marketplace for short-term lodging (e.g. *Airbnb*). (Owyang, et al., 2013)

2.2.4. Non-profit, fractional and community-based systems

Communal and fractional type of car-sharing is becoming popular in some developed countries since the 2010s. Differently from the aforementioned three types of car-sharing, this is organized mostly as small-scale non-profit initiatives. While the aforementioned three types of car-sharing are mainly employed in urban areas, this type of car-sharing is characterized by its use in rural areas. Organization of this can be as simple as completely non-technological one, while advanced organizers make use of ICTs such as web-based booking systems and on-board drive loggers.

A number of small municipalities take initiatives to introduce and organize this type of car-sharing for rural use. In some cases, municipal (official) car is put into a platform of car-sharing available for residents. This type of small-scale public car-sharing can also be managed by organizations other than municipalities, such as private companies offering their company cars for residents in surroundings in the outside of their business hours, other types of non-profit organizations e.g. national park office, religious institutions, and so on. Similar car-sharing is possible also in housing estates, targeting residents and inhabitants living nearby. Technologically this is similar to the station-fixed type of car-sharing, with a coordinating company offering reservation, payment transaction and fleet management systems, while the ownership structure is somewhat similar to peer-to-peer car-sharing. (Shibayama, et al., 2013)

2.3. Bike-sharing

2.3.1. Station-based

A prototype of bicycles was developed early in the 19^{th} century, and bicycle in today's form already became popular around the end of the 19^{th} century (e.g. Ebert, 2010). A systematic sharing of bicycles was attempted through many trial and errors in various places already since the 1960s. What is known as the first documented bike-sharing scheme is the *White Bike* in Amsterdam in 1965, with which 50 white-colored unlocked bicycles were made available for citizens. Later, the system with deposit-based one appeared, such as *Bycyken* in Copenhagen, which commenced into service in 1995. These first and second-generation systems faced various problems, and among many vandalism was a particular problem. (Dechant, 2013, Rappler, 2013)

The modern operational model of bike-sharing became widespread first after 2000. In this third generation model, bikes are stationed at electronically equipped docking stations, and users registered into the system with their authorized payment information such as credit card or bank account can rent a bicycle at one of docking stations, and return at the same or another station. As for financing, fees from the users and subsidies are combined. As for subsidies, various sources are in use such as direct subsidies, income from advertisement contracts (billboards and/or on bicycles), sponsoring, parking enforcement incomes and road pricing incomes. This model penetrated into many of European cities with some large-scale services implemented in Lyon with service commencement in 2005, Barcelona and Paris with service commencement both in 2007. With experiences longer than a decade, fixed-station bike-sharing has been added as an additional transport mode in many cities, with a higher level of acceptance and offering supplementary function to public transport. (Buettner, et al., 2011, Lemmerer, et al., 2014, Leth, et al., 2017)

2.3.2. Bike-sharing – dockless, free-floating

A newer variation of bike-sharing is a dockess and free-floating type of bike-sharing. An earlier example of such systems appeared in Germany as *DB Call-a-Bike*, which has been run by the railway company. Users will receive digital one-time authentication code via SMS or a phone call, and later also via its smartphone app, to unlock and lock bicycles. Although it has been in operation for a long time in Germany, this system did not get widespread.

More recently, with the diffusion of smartphones enabling easy-to-use map-based apps to locate available bicycles nearby, such dockless free-floating bike-sharing is becoming rapidly widespread on a global scale, mostly operated by Chinese companies. This boom started since around 2015, after the establishment and rapid development of two major players in this market, namely *Ofo Bike* (established in 2014) and *Mobike* (established in 2015). This is on one hand a still rapidly developing part, while on the other hand it is somewhat unstable part of new types of mobility service, with one of the main operator ceasing its operations in many of the countries because of financial difficulties. Differently from *Call-a-bike*, the market penetration of these new free-floating bike-sharing service is massive and rapid, bringing about various controversy such as inadequately parked bicycles blocking sidewalks, public transport stops, and barrier-free accesses, and abandoned shared bicycles in urban peripheries.

2.4. Motorcycle sharing and Scooter sharing

Similarly to car-sharing and bike-sharing, vehicle sharing of motorcycle and scooters are available nowadays. It started in 2012 in San Francisco, and since around 2015, it has been diffusing mainly in Germany, Spain and France, targeting young users. The system employs mostly free-floating system, and electric scooters. (Howe and Bock, 2017)

3. Ride-sharing

3.1. Ride-sharing (Car-pooling)

The idea of ride-sharing, also known as car-pooling, was conceived already in the 1940s. Spontaneous organization of ride-sharing, known as *slugging* or *casual car-pooling*, has been taking places in several cities in the United States including San Francisco Bay Areas, Washington DC, and Houston since the 1970s, when the oil price was suddenly increased and, and particularly in the context of the United States, oil embargo hit the country. This is often motivated by reduced toll for high-occupancy vehicle (HOV) lanes: drivers and passengers meet at specific areas to enable a shared ride to make use of advantageous toll for HOVs. This has been widely used by commuters, while it ran without any institutionalized platform: it is considered to be a custom or “naturally happening” behavior of commuters. (Carrese, et al., 2017, Oliphant and Amey, 2010).

In the late 1990s and the early 2000s, more organized form of ride-sharing appeared with help from diffusion of the Internet, and it became particularly popular for medium-distance and long-distance shared rides. Online marketplaces are provided by various companies such as *BlaBlaCar* and various *Mitfahrzentrale* in Germany to match driver and passenger having same destinations or destinations en route, and such marketplace are organized either as non-profit initiatives or commercial websites. This type of more institutionalized ride-sharing offers reliability on one hand as a shared ride is assured in advance and drivers can be rated by passengers, and accountability and trust is also provided as passengers can make use of rating of driver by previous passengers.

Recently, so-called “real-time ride-sharing” penetrates into the market with advancements of smartphones, which enables to form ride-sharing more spontaneously compared to the above-mentioned Web-based systems. It makes use of the geo-location of drivers and users, which come from geo-location-enabled smartphones used by drivers and travelers. The driver and the passenger are matched dynamically on an online platform making use of the real-time location of vehicles and the passenger. A social network embedded in the platform helps establishing trust and accountability between them. This system is called with various alternative names, such as dynamic ridesharing, instant ridesharing, on-demand ridesharing, and dynamic carpooling.

3.2. Ride-sourcing (ride-hailing)

Ride-sourcing refers to transport services that connect community drivers, who drive privately-owned cars, with passengers via a mobile app on smartphones (Jin, et al., 2018). This type of service such as *Uber* and *Lyft* appeared around 2010, along with the rapid diffusion of smartphones. Similarly to the real-time ride-sharing, the matching of the driver and the passenger is done with GPS-enabled smartphones. Some app provider offers an option to share a ride with other passengers with a same destination. The main difference from ride-sharing is that, in case of ride-sharing, the driver him- or herself is a traveler with a trip purpose at destination, while in case of ride-sourcing the driver's main purpose is to offer a ride. While the companies offering this type of service is expanding rapidly into many countries, some countries considers this as an illegal taxi. Ride-sharing websites are considered to be an intermediate match-maker, while ride-sourcing is considered as a transport service providers and thus subject to transport regulations. (OECD, 2018)

Of note, ride-sourcing is a term used more by administrators and academics, while practitioners call this "transportation network companies" or "mobility service providers". In everyday language as well as in the press, this is called "ride-sharing" or "ride-hailing", and many of this type of service advertise themselves using one of these terms, bringing about some confusions in terminology.

The aforementioned literature by Jin, et al. (2018) seems one of the first attempt to analyze the impact of this kind of service on urban efficiency by comparing ride-sourcing with taxis and public transport, on urban equity focusing e.g. on transport equity and discrimination, and urban sustainability from viewpoints of private car ownership and energy consumption as well as from greenhouse gas emissions.

4. App-based and online services

4.1. Online journey planners for public transport and satellite navigation system for automobiles

With diffusion of personal computers, digital timetable and journey planner as offline software became available for large cities already in 1980s, such as *Eki-Spart* dedicated for Tokyo. The first planner typically focused on large cities with complex railway network, and gradually it was extended to cover wider area, such as entire Swiss and German railway network (e.g. *HAFAS*) or entire Japanese railway network (e.g. *Eki-Spart*). When the Internet is becoming popular, such journey planners became available online in the middle of 1990s. The initial focus was on railways, while gradually other public transport modes and advanced search options such as search from street addresses and points of interests are added. (HaCon Ingeniuergesellschaft mbH, 2018, Val Laboratory Cooperation, 2008)

Slightly earlier than this, since the 1970s, on-board satellite navigation systems for automobiles were developed. In 1993, the Global Positioning System (GPS) reached to a full constellation and became available for provision of Standard Positioning Service, and the on-board navigation system combining satellite-based positioning, calibration with on-board sensors, and digital offline maps became popular. Online digital maps became popular with the diffusion of personal computers and the Internet in the late 1990s to early 2000s, and similarly to the on-board navigation they started to offer route search for automobiles. Along with the diffusion of GPS-enabled touch-screen smartphone since 2007, online navigation system on mobile devices is becoming available as smartphone apps.

As the latest development, multimodal journey planner became popular, either as a private initiative such as *routeRANK* in Switzerland and *navitime* in Japan, or as a public initiative such as *AnachB*, a journey planner offered by a public consortium in Austria. Such systems combine the features of railway/public transport journey planners and automobile route search, and sometimes similar road-based search for bicycles and walking. Some advanced system offers intermodal search, offering search of different transport modes combined in one trip chain such as park-and-ride and biking with on-board bicycle transport on railways.

4.2. Integrated public transport tickets, online ticketing and ticket apps

The idea of integrating public transport tariffs into one dates back to the 1960s without any advanced ICTs available (Krause, 2009). Day, month or annual pass for public transport networks has been offered in a form of paper ticket or plastic cards. Such concept is known by different names, while essentially important is that passengers can travel by public transport with one single tariff and thus thoroughly issued tickets, even if a trip calls for using several different companies' services within a trip chain. Such integration is organized as cross-acceptance of tickets in an earlier phase, and then as private-law contracts managed by an association. Recently, such association is entitled to coordinate public transport services within its area. (Ostermann and Rollinger, 2016) This tariff integration forms one of the important bases of the subscription model of MaaS, which we will see in Section 4.4 more in detail.

Since around 2000, online issuance of railway and public transport ticket instead of at ticketing counters or vending machines is made available for passengers. Where the ticket barrier is installed, online purchase and "pick-up" of the magnet-strip ticket from the ticketing machines at railway stations became widespread, such as in the UK and Japan. Where no ticket barrier is installed at railway stations, "pick-up" from the ticketing machine or counter and delivery by post were used at the beginning, but self-print tickets with 2D barcodes, which are delivered by e-mail or simply downloadable on the Web, diffused. In both cases, such ticketing is often integrated with online journey planner, and passengers can search connections with it first, and can purchase an appropriate ticket for the journey.

With diffusions of smartphones, ticketing on smartphones is becoming possible since around 2012 with 2D QR codes which can be validated by a device of conductor where no ticket barrier is installed. With this, users can search connections with journey planner app on a smartphone first, and then they can purchase corresponding tickets directly on the app. The latest smartphones support standardized passes, often called *digital wallet*, with 2D QR code, which can be used for ticketing of various services not only limited to public transport but also to museums, and events.

4.3. NFC cards

Since the late 1990s, introduction of NFC cards (near-field communication cards) to collect public transport fare is becoming popular, with Hong Kong's Octopus Card being probably the first widely-used one in the world implemented in 1997. Since then, such NFC "smartcards" have been introduced and widely in use in various places. The first ones are rather designated for the "closed" public transport systems, where passengers have to go through ticket barriers, while in the later phase the card is also introduced for "open" public transport systems, where passengers have to "check-in" at the origin, get controlled on board, and "check-out" at the destination. The NFC cards are also used for transport modes other than public transport, in particular bike-sharing and car-sharing. The latest development of smartphones with integrated NFC functions made it possible to put this on mobile devices.

With NFC cards, new types of public transport tariff are made possible that used to be technically difficult with paper-based and magnetic-strip tickets. The price-cap system is one of such examples, with which passengers first pay single-journey tariffs, while maximum amount charged per day, month or year is fixed and passengers can travel as if they were in possession of a day, month or annual pass. Such price cap system is in use, for example, in London for urban transport, and in South Tyrol for regional public transport.

4.4. E-hailing

Apps to "hail" a traditional taxi available nearby on mobile devices are becoming readily available (e.g. *MyTaxi*) and used already widely in many places on the globe. Technologically, this is similar to the ride-sourcing apps, while it works as a matching service between a passenger and traditional taxi service.

4.5. MaaS and single-stop service integration app

MaaS – mobility-as-a-service – is defined by its promoters as "the integration of various forms of transport services into a single mobility service accessible on demand" and aims at offering a single application and a single payment system to integrate all of the above-listed mobility services so that a comparable convenience to a use of automobile is provided (MaaS Alliance, n.d.)

Essentially, MaaS is a concept to aggregate various conventional and new types of transport services including aforementioned shared and app-based services, such as regular and on-demand pubic transport, car-sharing, ride-sharing, bike-sharing, taxi, and so on into one user interface accessible via smartphones. Such concept has been studied since around 2012, and gradually developed as real-world apps with services gradually added into one single app for each particular region (For example, as for Austria, see e.g. Neue Urbane Mobilität Wien GmbH, 2015, Der Standard, 2016). User may select which service provider they enable or subscribe. Besides classical as-you-go and flat-rate charging models, new types of payment packages are proposed: an example package is proposed including an annual pass of public transport, up to 100 km of taxi or ride-sourcing use, up to 500km of car-sharing, up to 1,500km ride of long-distance public transport, and 20 hours of use of shared bike included. (Hietanen and Sahala, c.a. 2016)

Several organization models are manifested, namely a single independent aggregator, an integrated public transport works as an aggregator and a "roaming" model that various MaaS aggregator coexists. For example, Vienna takes the second type of the approaches that the largest public transport operator in the city launched an integrated smartphone app that works as a one-stop app covering multimodal journey planners, public transport service subscription (annual, monthly and weekly pass) and single tickets, car-sharing (at the time of writing this paper, free-floating ones only), rent-a-car, bike-sharing schemes, taxis, and parking garages (Wiener Linien, 2018). Another example is Helsinki, where an independent aggregator company provides such an app for the city, strongly backed up by the municipal government (MaaS Global Oy, 2018).

To provide a meaningful MaaS app, availability of a wide range of non-automobile mobility services is a prerequisite, because MaaS itself is conceived as an aggregator for them. To enable an integration of public transport with "subscription" types of charging models, integration of public transport tariff seems well established because of decades of experiences in it since the time without ICTs, while subscription models for other types of modes integrated on MaaS seems still under development. In addition, availability of application programing interfaces (APIs) of integrated modes such as car-sharing and bike-sharing platforms, taxi haling apps, ride-sourcing apps, is another prerequisite to enable a single-stop service integration app, while this also seems an ongoing process.

5. Vehicle technologies

5.1. Connected Car

A *connected car* is an automobile that is equipped with wireless connection to the Internet. Various applications are made possible with this, as telematics are enabled between a vehicle and infrastructure (vehicle-to-infrastructure, V2I), surrounding vehicles (vehicle-to-vehicle, V2V), information made available on the Internet, often referred to as *cloud* (vehicle-to-cloud, V2C), and potentially with pedestrians with mobile devices (vehicle-to-pedestrian, V2P). Vehicle-to-everything or vehicle-to-X (V2X) refers to connection with anything that interferes with vehicle and it incorporates aforementioned and other specific types of telematics communications.

For the Internet connection, the wireless local area network (WLAN, also called Wi-Fi) technology was sought initially to form vehicular ad-hoc networks (VANETs): as an enhancement of the IEEE 802.11 standards, which is typically used for WLAN computer communication, a technical standard for VANETs is set as IEEE 802.11p in 2010. This is referred to DSRC (dedicated short-range communication) in the US, and ITS-G5 in Europe. More recently, use of the cellular network, primarily the 4G (LTE) network, is sought to enable V2X connections: this type is sometimes called C-V2X (Cellular V2X). At large, the connectivity to the Internet is similar to today's smartphones, which makes use of cellular networks and WLAN for wireless data transactions.

Initially, applications for safety is much on focus, such as *ERA-GLONASS Accident Emergency Reponses System* in Russia, which is required for cars sold in Russia since 2017, and *eCall* system established and made mandatory by the European Union in 2018: these systems automatically contact emergency services and informs the vehicle locations in case of severe accidents. Locking and unlocking of automobiles are made possible via smartphones, and such function is already deployed in car-sharing vehicles. Further potential applications include traffic information, service information e.g. parking and petrol stations, vehicle diagnostics functions, and so on: these are functions considered for single vehicle. Collaborative applications among vehicles include various driver assistance systems such as collision avoidance system, lane departure warning system, platooning (vehicles following another vehicle), and so on. (Viereckl, et al., 2014, Parker, et al., 2017)

5.2. Automatic driving and autonomous vehicles

Various industrial market research repeatedly estimates that sooner or later the self-driving (autonomous) vehicles will be available in the market (e.g. ERTRAC, 2015, Automotive Council UK, 2017). Commonly, such autonomous vehicles are classified into five levels by different extents of automation (SAE International, 2018):

- Level 1 refers to a partial automation of driving, such as adaptive cruise control, automatic emergency breaking, and lane centering, but calls for much human control.
- Level 2 refers to two functions being automated e.g. adaptive cruise control and lane centering automated.
- Level 3 refers to conditional automation with monitoring by a human driver. Automated driving is possible in a limited condition that does not call complex sensing of vehicle environments, such as low traffic volumes and non-extreme weather with high visibility, and so on. Monitoring by a human driver is needed.
- Level 4 refers to full automation performed by vehicle in approved situations, while control by drivers may still be required in some portion of each trip. In limited conditions, automated driving is possible, while in complex and unapproved situations human drivers have to control the automobile.
- Level 5 refers to complete automation without human control in any situations. The user inputs the destination, and the vehicle automatically navigates to the destination without any human control.

By this SAE definition, automated driving system (ADS) refers to the Levels 3, 4, and 5, while ADS-dedicated vehicles, often referred to as self-driving or autonomous vehicles, refers to the Levels 4 and 5, which enable driverless operation of vehicles partially or entirely throughout trips.

As for the market penetration, a majority posits that the Level 4 will not be readily available in the market before 2022 or 2023, and the Level 5 vehicles will be available much later than that, around 2030 at earliest. (ERTRAC, 2015, Automotive Council UK, 2017, Kuhnert, et al., 2017)

Technologically, autonomous vehicles incorporates various technologies from different domains, such as sensing technologies, artificial intelligence, geo-location, vehicle-to-everything connectivity, reliability engineering, human-machine interface, and so on (Suda and Aoki, 2015). Sensing technologies to monitor vehicles' surrounding environments include radar, lidar (*light detection and ranging*, a method to measure distances to an object by illuminate it with pulsed laser light, and then by measuring the reflected pulses), and computer vision. Various position and location sensors such as IMUs (*internal measurement unit*, a device that combines accelerometers and gyroscopes to measure its force and angular rate), GPS and odometers will enable highaccuracy geo-location, and advanced control systems make use of sensory information from these. For navigation based on geo-location, it also relies on detailed 3D digital map with exact positions of relevant objects on roads such as lanes, curbs, and traffic signs, while recent research seeks to navigate an autonomous car without it (Conner-Simons and Gordon, 2018).

5.3. Connected, autonomous cars and shared forms of mobility

Wireless connectivity (connected cars) and automation (autonomous vehicles) are essentially different concepts. The lower-level automation can depend largely on data from sensing devices on board and thus can work offline. They are however envisioned to be coupled as developments of both are taking place concurrently. The higher-level automation will be benefited from information that can be wirelessly transmitted such as latest digital maps and real-time traffic information, and from various applications. This will further be coupled with an advancement of battery technologies to enable electric automobiles. At large, the automobile is expected to become connected and autonomous, with electric motors.

Ownership structure of automobiles is expected to change, too. It is envisioned that connected and self-driving cars will be used more in a shared manner, either in a form of car-sharing or ride-sharing, even if the price of autonomous vehicles is reduced with technological advancement. As for the time-division sharing (car-sharing), the *connected* feature makes it easy to organize car-sharing since vehicles can be accessed and controlled by users' smartphones. Ride-sharing with connected and autonomous vehicles is expected, too, as dispatching of vehicle on demand specified by users via smartphones will be made possible with the envisaged features of *connected* and *autonomous* vehicles: such features are sometimes named as *robotaxis*. (Leslie, 2018, The Economist, 2018, Ceille, n.d., Hanna, et al., 2016)

Connected and self-driving vehicles will have some potentials to change the cost structure of public transport: small-scale scheduled or on-demand public transport are posited to be more affordable as less or no personnel cost of drivers will be incurred with a higher-level automation. This would make public transport services implementable in a low-demand area that would not otherwise be affordable, such as periphery of urban areas, small cities and towns, and in rural areas as well as to enable last-mile access/egress with it. Real-world tests have been carried out widely, particularly in Europe and in East Asia. (See e.g. Becker, 2018, Wiener Linien, 2017)

The driverless operation of automobile enabled with higher-level autonomous driving is expected to bring about a variety of new issues not only on traffic but wider ones ranging from legal issues to urban planning issues. Among legal issues include traffic regulation and liability, as well as "new" issues such as data protection and privacy (e.g. Parker, et al., 2017). Regarding road traffic, it will potentially bring about new types of vehicular trips on the street, such as zero-passenger vehicles. Such empty-running vehicle may induce extra traffic on roads and thus limiting available capacity, consuming extra energy, and at large leading to insufficiency in traffic.

6. Dependency and timeline analysis, and implications for transport planning

6.1. Key ICTs enabling emerging types of mobility services

In the previous sections, we reviewed new types of mobility services which appeared since around 1990s, subdivided by vehicle sharing, sharing of rides, online and app-based services, and vehicle technologies. Among them, vehicle sharing, sharing of rides and online and app-based services are the ones that have already been implemented and exist nowadays, while the vehicle technologies we focused on are rather the ones to come in the next decades.

Many of the existing types of services are enabled by diffusions of several key information and communication technologies (ICTs). The latest epoch-making device is the smartphone, which features a touchscreen as its primary user interface, apps (easy-to-handle software running on it), mobile Internet connection, and geo-location information available on device. First of this kind appeared in 2007, when LG and Apple put their first-generation smartphones, *LG Prada* and *iPhone* respectively, into the market.

Smartphones are essentially synthetic devices that integrate various key ICTs that diffused since the 1990s. Mobile Internet connections were made available in the late 1990s, when mobile broadband Internet (often referred to as *3G*) was made available. Mobile phone with basic data services (e.g. SMS) was already available before that, nowadays often referred to as *2G*. Such mobile application making use of the Internet is largely based on World Wide Web (WWW) and e-mail services, which were initially developed for desktop PCs and wired Internet connections. Of note, desktop PCs and the Internet diffused for households in the middle of 1990s, when *Windows* operating systems targeting home use (in years 1995 and 1998 respectively) and *iMac* (in 1998), as well as widespread Web-browser such as *Netscape Navigator* (in 1994) and *Internet Explorer* (in 1995) came into the market. Personal computer itself first appeared in the 1970s, and gradually stared to diffuse for office and home use since the 1980s.

The geo-location feature is nowadays supported by various GNSS (global navigation satellite systems) and location database of mobile phone masts (cell sites). Among several available GNSS, Global Positioning System (GPS), which was developed in the United States and made available for civil use in 1993, is the first one.

Several services made available with these ICTs, namely online digital mapping and online payment systems, play also important roles for the above-mentioned mobility services. Digital mapping (a kind of Geographic Information System in a broader sense) has existed since decades ago, while it was made available on personal computers in the 1990s (e.g. *MapInfo for*

Windows, in 1990), and made available online in early 2000s. (e.g. *Google Map,* made available for desktop PCs and mobile devices in 2005, (e.g. Koyama, 2017)) Online digital map makes it possible to provide actual maps for the end users, with continuous update carried out on the server side.

Another important service made available for consumers is online payment systems (e-commerce payment systems), partly coupled by diffusion of credit cards. Besides the use of credit cards, bank payments enabled by Internet banking and various online payment service provider (e.g. *PayPal, Alipay, etc.*) are available as electronic payment system for consumers. Both of these started to be available since the late 1990s and early 2000s. NFC-cards used for payment can be nowadays coupled with these kinds of online payment services, and in the latest development it starts to be integrated into smartphones.

Many of the new and emerging types of mobility services depend on these key ICTs mentioned above, namely personal computers, GPS, The Internet and WWW, cellular network enabling mobile phone with data service (SMS), online digital mapping, online payments, NFC cards, broadband cellular network with Internet-enabled mobile phone, and smartphone to a large extent. For several mobility services, some ICTs are not prerequisites while they can be deployed or they are stimulators for wider diffusion.

Among the vehicular technologies discussed in Section 5, cellular network enabling broadband Internet connections is one of the key ICTs enabling connected cars. Smartphone is an essential prerequisite, as the concept of mobile Internet connectivity is first realized in this form, and initial implementations are made as tethering smartphones to automobiles. As for autonomous driving, GPS is one of the key technologies for precise geo-location of automobiles, and 3D online digital map probably will remain essential. For the connectivity to the Internet, similarly to the connected cars, broadband cellular network is an important prerequisite.

Based on the review presented in the previous sections, dependencies of new and emerging mobility services and vehicular technologies on various ICTs mentioned in this section are summarized in Table 1. Here, some of the mobility services mentioned above (e.g. Non-profit, fractional and community-based car-sharing and scooter sharing) are excluded because they are still in niche markets compared to the others.

Table 1 Dependencies of new and emerging mobility services on various ICTs

Key ICTs	Personal computer	GPS	The Internet / WWW	Digital cellular network, mobile phone with data service (SMS)	Online digital map	Online payment	NFC card	Broadband cellular network, internet-enabled mobile phone	Smartphone
Car-sharing, fixed station		✓	+		+	+			+
Car-sharing, free-floating		✓	+		✓	✓			✓
P2P car-sharing			✓		✓	+			
Bike-sharing, fixed station		✓				✓			
Bike-sharing, free-floating		✓		✓	✓	✓		+	✓
Ride-sharing marketplace			✓			+			
Ride-sourcing			✓		✓	✓			✓
Tariff integration of PT									
Offline journey planner	✓								
Online journey planner			✓		+			+	+
On-board car-navigation		✓	+		+				
Online ticketing (pick-up, self-print)			✓	+		✓			
Ticketing on mobile app						✓	+		✓
MaaS		✓			✓	✓	+	✓	✓
Connected cars					+		+	✓	✓
Level 4 &5 self-driving vehicles		✓			✓			✓	+

Legend: ✓: Indispensable prerequisite; +: value-adding feature (nice-to-have)

6.2. Development timeline

Making use of the result form the review and the results presented in Table 1, technological dependencies is summarized in a form of timeline. Besides the dependency of mobility services on ICTs, dependency of mobility services on previously available services are also analyzed: for example, online journey planners depend much on offline journey planners, which was available earlier, and ride-sharing marketplaces depends on an idea of slugging (casual carpooling). MaaS as an aggregator depends largely on various existing services, such as integrated public transport tariff and annual passes and various vehicle-sharing and ride-sharing services. These types of relations are diagrammatically shown in Fig. 1.

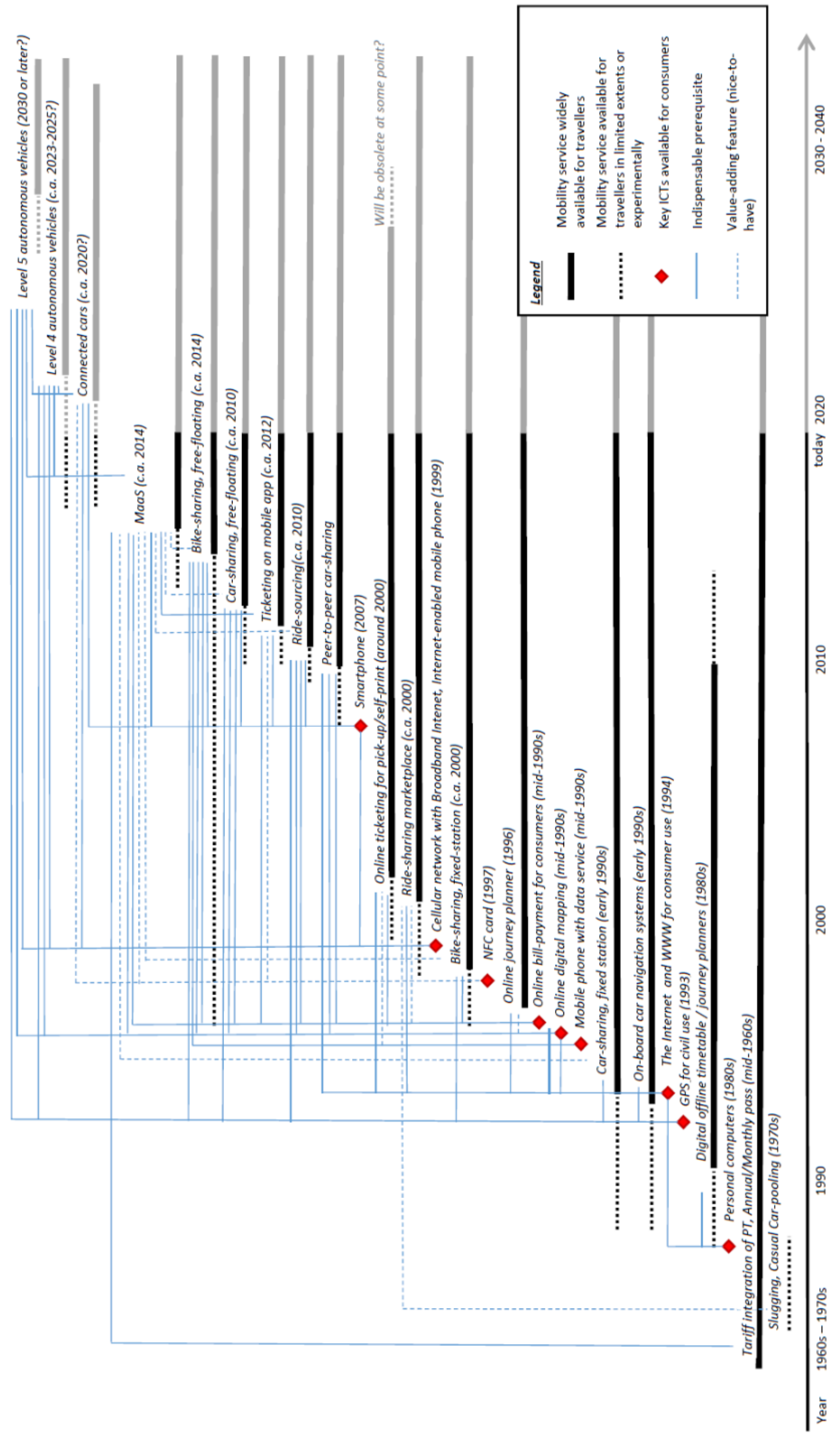

Fig. 1. Timeline analysis of various emerging mobility services, vehicular technologies and ICTs.

Several remarkable dependencies are pointed out. First, free-floating bike-sharing, which has been booming since around 2014, depends much on technologies that are available since the middle of the 1990s, while employment of smartphones made it possible to put it into the mainstream. There is a gap of about two decades between availability of key technologies and diffusion. This is probably because of the low operability of mobile devices before the time of the smartphone: diffused mobile phones at that time only carried keypads in a form of ten-keys, the “upstream” data from mobile devices to the server had to go via narrow-band cellular networks and often in a form of SMS, and geo-location of mobile devices was not enabled. Smartphones solved these problems with touch screen, embedded geo-location services, and pre-installed standard Internet protocol enabling “apps”. Similar things can be observed with ride-sourcing. This implies that availability of easy-to-use user interface plays a key role for diffusion of a new type of services.

Secondly, many of the key information and communication technologies were made available already in the 1990s, while the employment of them for various new types of services ranges much longer, and many of them came into reality after 2000. Not surprisingly, for many of emerging mobility services, smartphones, which came into the market in 2007, play important roles as enabler for many types of services, namely peer-to-peer car-sharing, ride-sourcing, ticketing on mobile-app, free-floating car-sharing, free-floating bike-sharing, and MaaS. Ticketing on mobile-app is particularly benefited from its large and flexible display that enables display of 2D barcodes, which were already in use with self-printing online tickets and which enables easy on-board control of tickets. The others make use of its geo-location features to match the user and available vehicles or drivers nearby.

Among many key technologies, GPS (or satellite-based geo-location systems) and online digital mapping serve themselves as indispensable prerequisite for many of emerging mobility services and vehicle technologies. This is understandable as, to enable mobility services, as well as new vehicular technologies, precise identification of geographic location of available services will enable real-time dynamic information provision for the users about them, while making use of users’ geo-location will enable suggestion of best-matching travel options. Of note, geo-location can be identified by other means such as cellular masts and connected Wi-Fi networks in case of smartphones and odometers and other sensors in case of vehicles. Recent services and technologies combine these various information sources to identify geo-locations.

At large, until now employment of new ICTs has been taking place mostly separately for public transport and automobiles. This has been changing in the recent years, since journey planners is becoming multimodal, and as seen above MaaS is conceptualized as an aggregator of traditional services such as public transport and emerging services such as vehicle sharing, ride-sharing and ride-sourcing, and it is much benefited from the experiences of public transport integration. Considering that connected and autonomous vehicles are posited to be used more in shared forms, it is reasonable to estimate that this integration trend will probably continue in the future. From such integration perspective, future connected and autonomous vehicles will paradoxically depend on non-automobile services to a large extent that are becoming available nowadays.

6.3. Implications for strategic and long-term transport planning

From a viewpoint of strategic and long-term transport planning, several remarks and implications are pointed out. First, the emerging types of services becoming available today are still based on traditional modes, and thus they did not call for much change in traditional ways of strategic planning that has been in practice since the post-war time. The connected and autonomous vehicles will change this in long term because the today’s concept of private vehicles and public transport will be integrated along with the technological development of it. In other words, the importance of multimodal and integrated strategic planning will gain more importance in the future: separate planning for road infrastructure and railway infrastructure will not be much effective, as these two will be used in more integrated manner.

Many researches conclude that, with assumptions derived from today’s automobile ownership and usage as well as associated costs to them, traffic demand of autonomous automobiles will increase (e.g. Litman, 2019). However, these assumed ownership and usage may not be valid in the future as shared ownership is envisaged to a large extent, and availability of automobiles for individuals will change as a consequence. In addition, it is repeatedly reported in many developed countries that today’s young generation tend to have less interests in owning cars (e.g. Bratzel, 2011, Dalan and Doll, 2010). Coupled with this, the usage of automobiles in the age of high level driving automation will change from that of today: further research onto this is, however, needed to understand impacts of autonomous vehicles in ownership and usage of automobiles in the future. Infrastructural capacity that was envisaged as necessary in the past until today may have to be reassessed carefully: systematic methodologies to reassess existing plans in line with altered usage and car ownership structures will be called for on one hand.

On the other hand, optimization methodology of the existing road infrastructure will also have to be sought, such as reassignment of street space for vehicles to different use e.g. for pedestrians, cyclists and public transport or even as a surface for building in case of urban roads, or dismantling of road infrastructure that will no longer be necessary in case of rural or bypass roads to control the demand of vehicular traffic. In turn such retrenchment will help reduce vehicular traffic at large, and eventually help reducing negative effects of it such as noise and emissions as well as energy consumption.

In addition, as much of road infrastructure that was built during the rapid motorization in the 1960s and 1970s will come to the end of its lifetime in parallel with the technological developments of autonomous vehicles, such network redesigning and optimization will have to be coupled with this aspect, too. This is probably more difficult decision-making compared to make a decision to build something new as it may be negatively perceived and thus become contentious: policy guidance for such difficult decision will have to be researched in the future.

Optimization will also be needed in the domain of parking regulations, especially minimum parking requirements and pricing, because the total vehicle stocks may be reduced as the shared use of vehicles will diffuse more. More use of automobiles in shared manner will imply that the demand for parking will also be reduced: further research will be needed for this to guide such parking optimization. It has to be noted that this has to be coupled with measures to prevent zero-passenger self-driving automobiles roaming around the city to return to a parking spot in the outskirts of the city, which induces extra vehicular traffic.

7. Conclusion

In this paper, aiming to gain an holistic outlook about emerging types of mobility services and vehicular technologies as well as their dependencies on various information and communication technologies that are essential for strategic and long-term transport planning, we reviewed various emerging mobility services and vehicular technologies, namely vehicle sharing (Section 2), sharing of rides (Section 3), various online services (Section 4) and vehicular technologies (Section 5). Based on this, we analysed technological dependencies of these new mobility services and vehicular technologies on various information and communication technologies, and also carried out a timeline analysis based on it, as presented in Section 6.

Among vehicle sharing, four types of car-sharing are reviewed: station-fixed car-sharing, free-floating car-sharing, peer-to-peer car-sharing, and fractional and community-based car-sharing. Station-fixed bike-sharing, free-floating bike-sharing, and motorcycle/scooter sharing are also reviewed. As sharing of rides, ride-sharing and ride-sourcing are reviewed. As for app-based services, reviewed are public transport journey planners and car-navigation systems, which is being integrated as multimodal journey planner nowadays, online ticketing and ticketing apps, NFC cards, and e-hailing apps are reviewed. Here, as an aggregator, concept of MaaS (mobility-as-a-service) is also reviewed. Following this, the concept of connected cars and autonomous (self-driving) vehicles are briefly reviewed, too.

Various ICTs deployed for “new” mobility services were made available already in the 1990s, while employment for mobility services takes between approximately 10 and 20 years. Some “new” services had to wait until the diffusion of smartphones, which offers simple user interface while make it possible to run complex applications on users’ own mobile devices. The geo-location features enabled with GPS coupled with online digital mapping on mobile devices are one of the key enabler for various new mobility services. Until now, “new” services are separately conceptualized for public transport and shared services, while integration of them is already taking place. When connected and autonomous vehicles with higher level of driving automations become available, shared use of them will become more common instead of private ownership of automobiles: in this context, the technology originating in private vehicles has potentials to become further integrated with the services originating in public transport and shared services in the future, based on integration of them that is attempted today.

Several implications are gained for strategic and long-term planning with autonomous vehicles envisaged to be used more in shared forms: this will enable higher efficiency in usage of road capacity, eventually leading to fewer needs for road infrastructure stock to support a same level of human mobility involving vehicular traffic. Optimization of road infrastructure including reassignment of road space for different use than today, such as for non-vehicular modes, public transport, or even as general urban land use has to be sought in cities: as such, “sliming” of existing road will also be a potential option. This is also needed from a viewpoint of the timing that the envisaged development of autonomous vehicles and the end of the lifetime of infrastructures build during the rapid motorization phase will take place in parallel. At large, multimodal strategic planning will gain more importance, while methodology and policy guidance for this type of decision-making will have to be researched more in the future.

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