REPORT
The digitalization of passenger transport

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Technologies, applications and potential implications for greenhouse gas emissions

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Mistra SAMS
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Abstract

To meet internationally agreed climate protection targets, a drastic reduction of passenger transport greenhouse gas (GHG) emissions is required. The “Avoid-Shift-Improve”-Approach suggests to meet future transport demand by avoiding unnecessary travel, shifting travel to more environmentally-friendly transport modes and improving the environmental performance of transport modes. Digital applications can contribute to both an increase or a decrease of passenger transport GHG emissions, e.g. by avoiding travel, increasing travel or shifting travel to more GHG-intensive or GHG-efficient transport modes. In view of the large number of digital applications in passenger transport and their uncertain impacts on GHG emissions, the aim of this report is to present a review of (1) digital technologies that are used in passenger transport, (2) applications that are supported by digital technologies and (3) their potential impacts on GHG emissions.

We identified nine central categories of digital technologies that shape passenger transport, namely (mobile) end user devices and apps, telecommunication networks, cloud computing, artificial intelligence and big data, geospatial technologies, digital sensors, computer graphics, automation and robotics and blockchain. These technologies support various applications in passenger transport which can be categorized into digital traveler information systems (e.g. trip planning and booking apps), digital shared mobility services (e.g. car or ride sharing), digitally-enabled transport modes that would not exist without digital technologies (e.g. virtual mobility, taxi drones), digital in-vehicle applications (e.g. automated driving), and digital applications for traffic and infrastructure management (e.g. traffic simulations and mobility pricing).

All described applications can have reducing and increasing effects on GHG emissions. Main levers to reduce GHG emissions are (1) a reduction of number of vehicles produced (e.g. through vehicle sharing), (2) a reduction of total travel distances (e.g. through virtual mobility), (3) an increase in the attractiveness of and shift to more GHG-efficient transport modes (e.g. through multimodal mobility platforms), (4) an increase in the utilization of transport modes and a reduction of vehicle kilometers traveled (e.g. through ride sharing), and (5) an increase in the fuel efficiency of vehicles (e.g. through automated driving systems).

In a real-life setting, the impacts of digital applications depend on the interplay between the applications and their design, existing travel patterns and the policy framework in place. In order put digital applications in passenger transport at the service of climate protection, applications and policies have to be aligned in a way that they promote GHG reducing levers. Otherwise, there is a risk that these applications lead to an increase in GHG emissions, e.g. by inducing additional travel or promoting more GHG-intensive transport modes.

Future research should empirically assess the impacts of digital applications on passenger transport and identify the conditions under which decarbonization potentials will materialize. This will support policy makers and market actors to jointly create conditions under which offering digital applications in passenger transport contributes to a net GHG emission reduction and is economically-feasible.

Keywords
Transport, mobility, digitalization, information and communication technology, climate protection, greenhouse gas.

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1 Introduction

1.1 Background and research aim

Digitalization, the societal change driven by use of information and communication technology (ICT), penetrates almost all economic sectors and domains of everyday life (Bieser & Hilty, 2018; Brennen & Kreiss, 2014). A sector, that is particularly subject to ICT-driven change is passenger transport. Digital technologies and applications impact passenger transport in diverse ways. For example:

- Automated driving systems will fundamentally change the way we use cars in the future (Taiebat et al., 2019).
- Mobility-as-a-Service (MaaS) platforms such as UbiGo or Whim allow to plan and conduct multimodal trips (Kramers et al., 2018).
- Virtual mobility solutions (e.g. video conferences, virtual reality) provide accessibility without physical presence and thereby avoid the need for physical travel (Bieser, Salieri, et al., 2020).
- Digital platforms for car and ride sharing allow us to access transport modes without owning the respective vehicles (Shaheen et al., 2020).

The number and types of digital applications in passenger transport is continuously increasing. For example, the number of mobile app downloads increased from 141 bn in 2016 to 218 bn in 2020 (Statista Research Department, 2021c), with “ride-hail & taxi”, “communication” and “travel booking” being among the fastest growing categories in 2018 (Statista Research Department, 2021a). The global market for intelligent transport systems (ITS) is expected to grow by 12.7% annually between 2015 and 2024 to reach a volume of 54 bn US-$ by 2024 (Intelligent Transport, 2018).

As the transport sector is one of the main contributors to global greenhouse gas (GHG) emissions (Sims et al., 2014), a drastic reduction of passenger transport GHG emissions is required to achieve nationally and internationally agreed climate protection targets such as the Paris Agreement (Paris Agreement, 2015). The “Avoid-Shift-Improve”-Approach[1] suggests to meet future transport demand not by providing additional transport infrastructures but by avoiding unnecessary travel, shifting travel to more environmentally-friendly transport modes and improving the environmental performance of transport modes (United Nations, 2016). Digital applications provide opportunities for avoiding travel (e.g. through video conferencing), shifting travel to more climate-friendly transport modes (e.g. through ride pooling platforms), and improving the GHG-efficiency of transport modes (e.g. by increasing the fuel efficiency of cars through automated driving systems). However, digital applications may also lead to an increase in passenger transport GHG emissions, e.g. if they induce additional travel or lead to a shift to more GHG-intensive transport modes (e.g. if digitally-enabled car sharing replaces public transport, Bieser & Höjer, 2021).

Thus, with the increasing digitalization of passenger transport and the urgent need to reduce passenger transport GHG emissions, a key question is whether and how digital applications can lead to a reduction of passenger transport GHG emissions. For transport decision makers, it is essential to obtain an overview of the state-of-the art in digital applications in passenger transport in order to systematically identify the most promising applications for creating the climate-friendly passenger transport of the future. This is equally important for ICT and transport researchers in order to assess the impact of digitalization on transport systems, e.g. in the form of technology assessments (Banta, 2009).

[1] The “Avoid-Shift-Improve”-Approach “was initially developed in the early 1990s in Germany as a way to structure policy measures to reduce the environmental impact of transport” (United Nations, 2016, p. 63).

While some studies have investigated specific digital applications in passenger transport (e.g. Amatuni et al., 2020; Gerte et al., 2018; O'Brien & Yazdani Aliabadi, 2020, 2020; Ringenson et al., 2018), the conceptual relationship between telecommunications and travel (Mokhtarian, 1990, 2002; Mokhtarian et al., 2006; Pawlak et al., 2015), or the GHG impacts of selected applications (e.g. Amatuni et al., 2020; Bieser et al., 2021; O'Brien & Yazdani Aliabadi, 2020), we could not find a comprehensive overview of digital applications in passenger transport and their potential impacts on GHG emissions. The aim of this report is to addresses this gap by pursuing the following goals:

1. Providing an overview of digital technologies that are used in passenger transport
2. Providing an overview of passenger transport applications that are supported by digital technologies
3. Identifying potential consequences of these applications for passenger transport GHG emissions

This report was created within the scope of the Mistra SAMS program, which is an 8-year research program to investigate how digitally-supported services for accessibility and mobility can contribute to a reduction of GHG emissions by the year 2030[2]. The results provided in this report will guide the selection of possible interventions for a planned living lab in the Botkyrka Municipality, Sweden.

1.2 Limitations

We focus specifically on applications that target everyday mobility needs (e.g. commuting, shopping trips). Applications for occasional and long-distance trips (e.g. holidays), for freight transport (e.g. delivery services), or applications supporting the electrification of passenger transport are out of scope of this report. Also, technologies and applications that provide auxiliary functionalities for another main application are not considered (e.g. vehicle control units). Even though we reviewed a vast amount of literature, further digital technologies and applications that impact passenger transport beyond the ones mentioned in this report exist. It is challenging to identify all existing technologies and applications as they continuously increase in number.

Our discussion of GHG impacts of digital applications does not consider the impacts of producing and operating the ICT hardware and software required for the applications and neither long-term, systemic impacts. Also, the "sustainability of passenger transport" depends on further indicators beyond GHG emissions, which have to be considered in holistic assessments of impacts of digital applications on the "sustainability" of passenger transport. For example, the European Commission (2020) distinguishes 18 core indicators of sustainable urban mobility including environmental indicators (e.g. energy efficiency and GHG emissions), social indicators (e.g. affordability of public transport for the poorest group, accessibility of public transport for mobility-impaired groups, road deaths) and economic indicators (e.g. congestion and delays).

Still, we hope that the overview of digital technologies and applications in passenger transport provided in this report supports transport researchers and decision makers in comparing existing applications and deriving strategies to align the digitalization of mobility with climate protection.

[2] https://www.sams.kth.se

2 Terminology

This section provides definitions of important terms and concepts used in this report.

Information and communication technology (ICT)

Bieser and Coroamă (2021) define ICTs as the entirety of technologies to sense, store, transmit and process information. We add actuating to the list of ICT capabilities as modern ICT applications often include components to transform data back into physical action via actuators (e.g. with displays or motors in robots, Table 1). Today, all these technologies have become electronic and digital. Thus, any information that can be digitally sensed and/or stored, can also be transmitted and processed (Hilty & Bieser, 2017), and often transferred into physical action via actuators.

Capability	**Description**	**Examples**
Sensing and actuating	Capturing information about the condition of objects and the environment and transforming it into digital signals (sensing) or transforming digital signals into physical action (actuating)	- Sensing: LiDAR sensors, GPS sensors, touchscreens - Actuating: Motors in robots, displays, virtual reality glasses
Storing	Storing large volumes of data	- DVDs, hard drives, USB-sticks - Cloud data centers
Transmitting	Transmission of data among people and objects over telecommunication networks	- Fixed telecommunication networks - Mobile telecommunication networks (e.g. 4G) - Low power wide area networks (LPWAN, e.g. Sigfox, Narrowband IoT)
Processing	Manipulating data to produce meaningful information	- Analytics software applications - Visualization software applications

Table 1: Capabilities of information and communication technology (ICT).

Digital technologies

Digital technologies is often used as a synonym for digital ICT or technologies that are largely based on digital ICT (IGI Global, n.d.).

Digitization, digitalization, digital transformation

The term digitization describes "the material process of converting analog streams of information into digital bits" (e.g. converting paper-based books into e-books). The term digitalization describes the societal process in which "many domains of social life are restructured around digital communication and media infrastructures" (Brennen & Kreiss, 2014, p. 1). Digital transformation can be used to describe "the transformative changes achieved through digitalization" (Bieser, 2020, p. 23).

Mobility, passenger transport, passenger transport modes and infrastructures

Mobility describes the movement of people. Passenger transport also describes the movement of people and the economic sector whose performance is often measured in passenger kilometers (pkm, FSO, 2020; OECD, 2021). Passenger transport modes are the different means available to people to travel from their origin to their destination such as walking, bikes, scooters, cars, or public transport. Public transport usually refers to a combination of transport modes including buses, commuter trains, metros and trams. Transport infrastructure refers to fixed installations for transport such as railways, roads, bus or railway stations (Hossain, 2019).

Sometimes, passenger transport refers only to motorized transport modes (e.g. car, bus or train, OECD, 2021). However, we consider all transport modes, including non-motorized modes such as walking or biking. Even virtual mobility (e.g. video conferencing) can be considered a transport mode that competes with physical transport modes (Hilty et al., 2004).

Accessibility

Accessibility describes the opportunity to participate in activities (Couclelis, 2000). Accessibility can also be achieved with ICT instead of physical travel (e.g. through video conferencing or remote access to data), often referred to as virtual mobility (Bieser & Hilty, 2018) or travel-free accessibility (Hårrskog et al., 2018).

3 Method

We identified digital technologies (3.1) and applications (3.2) that are used in passenger transport and analyzed potential consequences of these applications for passenger transport GHG emissions (3.3).

3.1 Digital technologies in passenger transport

To identify digital technologies we used the overview of information technologies that support mobility by Rodrigue (2020) as a foundation. The overview shows seven information technology categories, namely access devices, geospatial services, connectivity networks, open data exchanges, integrated payments, cloud services, and blockchain. To identify further digital technologies that are not part of this overview, we searched for further scientific and grey literature on Google Scholar and Google using (a combination of) keywords such as "digital technology", "information and communication technology", "ICT", "digital", "passenger transport", "mobility", or "smart mobility".

We discussed all identified technologies with researchers from the Mistra SAMS research program and from Ericsson Research who investigate the use of digital technologies in mobility. Based on the discussions, we added new technology categories to the overview by Rodrigue, dropped technologies because some of them rather described functions instead of technology categories (e.g. integrated payments) and adjusted the terminology (e.g. from "cloud services" to "cloud computing"). Finally, we clustered all categories by the ICT core capabilities they support, i.e. to sense, actuate, transmit, store and process information, and described each technology briefly.

3.2 Digital applications in passenger transport

To identify digital applications in passenger transport, we searched for scientific and grey literature on Google Scholar and Google using (a combination of) keywords such as "digital", "application", "digitalization", "passenger transport", "mobility" or "smart mobility". Identifying all applications and illustrating them in a comprehensible way turned out to be challenging as a vast number of existing digital applications are often described with varying terminology. Therefore, we clustered the identified applications into categories and described common applications in each category. We identified five clusters of applications that differ by their impact on transport modes and infrastructures (e.g. improving the performance or the management of transport modes) and the functionality they provide to citizens (e.g. providing information on schedules or access to vehicles without ownership). The clustering was also discussed and refined through discussions with researchers from the Mistra SAMS research program and from Ericsson Research.

3.3 Potential impacts of digital applications on passenger transport GHG emissions

To identify potential impacts of digital applications on passenger transport GHG emissions, we summarized drivers of passenger transport GHG emissions based on Sims et al. (2014) and identified mechanisms or levers through which the applications can lead to a reduction or an increase of GHG emissions, which is a common approach in environmental impact assessments of digital applications (Bieser & Hilty, 2018). For each of the identified application categories, we identified potential GHG increasing and reducing levers, aggregated the levers across all application categories and clustered them according to the three strategies to achieve sustainable transport systems stipulated in the "Avoid-Shift-Improve"-Approach (United Nations, 2016), namely to avoid unnecessary travel, shift travel to more environmentally-friendly transport modes and improve the environmental performance of transport modes.

Finally, we synthesized our results by discussing the relationship between the identified technologies and applications, their impact on GHG emissions, and summarized our main conclusions.

4 Digital technologies in passenger transport

Figure 1 provides an overview of nine categories of digital technologies that are used in passenger transport. The categories are clustered by the capabilities of ICT they support, i.e. *sensing and actuating*, *transmitting*, *processing*, *storing*. It shows that most technology categories support more than one capability of ICT.

Finding a set of technology categories that is comprehensive and mutually exclusive is difficult because of varying terminology to describe technologies, different ways of aggregating technologies into categories (e.g. machine learning can be considered a category on its own or a part of artificial intelligence, AI), and overlaps among technologies and categories (e.g. digital sensors are a category on its own but some sensors also support geospatial technologies). Thus, further ways of categorizing technologies and overlaps among the technology categories exist. The purpose of this illustration is to balance comprehensibility, comprehensiveness and demonstrate how the technologies relate to the core capabilities of ICT.

In the following, we briefly describe each technology category. A longer description of the technologies can be found in the appendix.

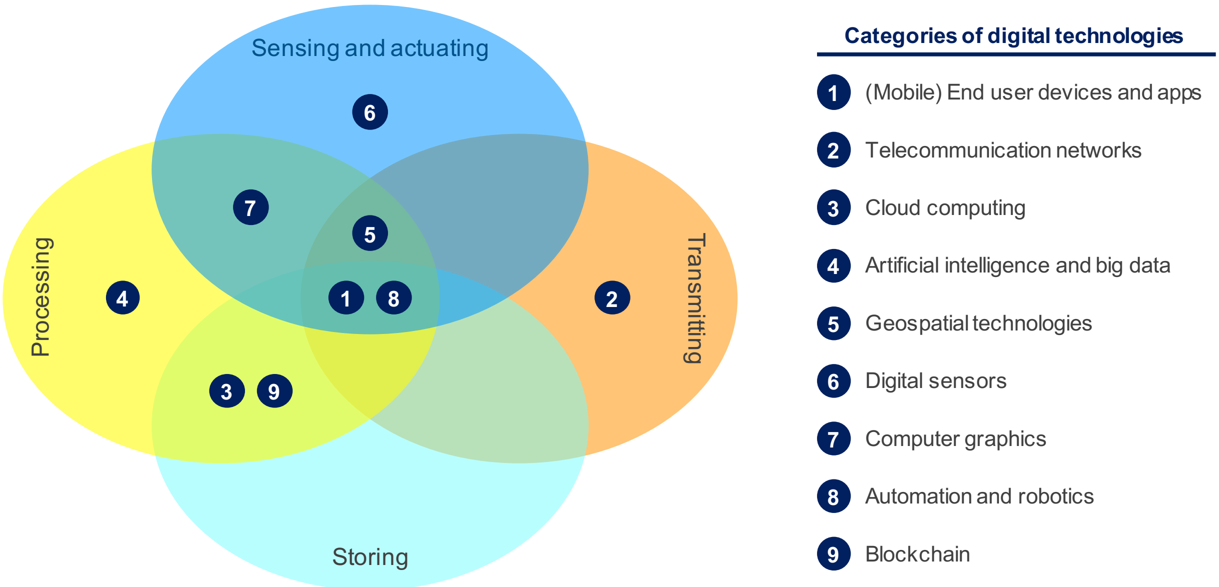

Figure 1: Categories of digital technologies in passenger transport clustered by the capabilities of ICT they support (adapted from Rodrigue, 2020).

4.1 (Mobile) End user devices and apps

End user devices such as desktop computers, laptops or tablets provide users the possibility to display *(actuate), process and transmit* data. Mobile end user devices such as smartphones or tablets can be used on-the-go and usually transmit data via mobile telecommunication networks (see 4.2). They are often also equipped with *sensors* (Anjum & Ilyas, 2013, see 4.6), e.g. GPS sensors, cameras, gyroscopes to capture data about the physical environment of the device which can be used by software applications.

4.2 Telecommunication networks

A communication network is “a group of devices connected to one another” and can be used to *transmit* data among devices (Grigorik, 2013, p. 80). Telecommunication networks can be distinguished in fixed and wireless networks. The Internet is a special type of communication network that uses the TCP/IP protocol to connect devices (Abbate, 2017) and that can be accessed via fixed and wireless networks. The Internet of Things (IoT) describes the phenomenon that not only people transmit data amongst each other (e.g. via computers or smartphones), but that objects are equipped with connectivity and exchange data amongst each other (Dorsemaine et al., 2015).

4.3 Cloud computing

Cloud computing describes the provisioning of ICT services (e.g. processing power, storage, software applications) in centralized data centers that can be accessed over the Internet (Repschläger et al., 2010). This means that data *processing* or *storage* no longer takes place on user devices (servers, computers, smartphones; user can be companies or end users), but in the data centers of the cloud computing service provider. The users then access the computing resources or application through an interface environment, e.g. through a web browser, on their device.

4.4 Artificial intelligence (AI) and big data

Various terms in this field exist, such as AI, advanced analytics, machine learning and big data, all of which circle around the possibility of analyzing (*processing*) large amounts of data to derive meaningful insights that could not have been derived with traditional data analysis techniques and smaller data volumes.

AI can be defined as “the ability of computers to perform complex tasks and exhibit human-like intelligence […]” (Samuylova, 2019, p. 1). Advanced analytics is “the autonomous or semi-autonomous examination of data or content using sophisticated techniques and tools […] to discover deeper insights, make predictions, or generate recommendations” (Gartner, n.d., p. 1). Machine learning “algorithms use large sets of data inputs and outputs to recognize patterns and effectively “learn” in order to train the machine to make autonomous recommendations or decisions” (Helm et al., 2020, p. 69). Machine learning can be considered a part of advanced analytics, which can be considered a part of AI. Big data describes large volumes of data from various sources that increase at a fast pace. Big data is used as an input for machine learning, advanced analytics or AI in general (Chandra, 2019).

4.5 Geospatial technologies

“Geospatial technologies is a term used to describe the range of modern tools contributing to the geographic mapping and analysis of the Earth and human societies” (AAAS, 2021, p. 1). Geospatial technologies provide the possibility to *sense*, *process*, *transmit* and visualize geospatial data. A geospatial technology that is intensively discussed in recent years is geofencing. “Geofences are virtual geographic boundaries that enable software and applications to trigger a response when mobile devices enter or leave a particular area” (Dabbs, 2018).

4.6 Digital sensors

“A *sensor* is a device […] that detects events or changes in its physical environment (e.g., temperature, sound, heat, pressure, flow, magnetism, motion, and chemical and biochemical parameters) and provides a corresponding output” (Rayes & Salam, 2017, p. 58). While analogue sensors produce a continuous output signal, digital sensors convert analogue to digital (discrete) output signals (Rayes & Salam, 2017; Thomas et al., 2015). Smart sensors are equipped with further components such as microprocessors and communication components that allow to trigger a reaction (e.g. send data) only when specific conditions are met.

4.7 Computer graphics

Computer graphics are “methods and techniques for converting data to and from a graphic display via computer” (Enderle et al., 1987, p. 2). It deals with creating visual representations out of formal descriptions (e.g. data), creating formal description out of visual representations and the *processing* of visual representations (e.g. images processing, Enderle et al., 1987). Computer graphics uses hardware such as monitors and graphic cards to transform data into optically-visible signals (*actuating*, Enderle et al., 1987). One of the main benefits of computer graphics is that “visually presented information can be accessed by human perception [...] in less time, in greater number, and with fewer errors than in any other way” (Enderle et al., 1987, p. 2f.).

4.8 Automation and robots

Automation can be defined as “the process of following a predetermined sequence of operations with little or no human labour” (Gupta & Arora, 2009, pp. 1-2). A robot can be defined as “an autonomous machine capable of sensing its environment, carrying out computations to make decisions, and performing actions in the real world” (*sensing*, *processing*, *actuating*, Guizzo, 2018, p. 1,). Robots are sometimes considered the most advanced or most visual form of automation (Ceccarelli, 2004; Gupta & Arora, 2009). Often, robots also exchange data (*transmitting*) with surrounding robots or a central unit which submits instructions.

4.9 Blockchain

A blockchain is a decentralized database that is mirrored in the network on a variety of computers. Entries (e.g. transactions) are summarized and *stored* in blocks. A consensus mechanism (*processing*) used by all computers ensures the authenticity of database entries (Mitschele, n.d.). Smart contracts are based on blockchain technology and “permit trusted transactions and agreements to be carried out among disparate, anonymous parties without the need for a central authority, legal system, or external enforcement mechanism” (Frankenfield, 2021, p. 1).

5 Digital applications in passenger transport

We identified five categories of digital applications in passenger transport:

1. *Digital traveler information systems*: Information systems that support travelers in trip planning and booking.
2. *Digital shared mobility services*: Services that provide temporary access to vehicles (and drivers) without ownership through digital platforms. Sometimes these services are provided by citizens, e.g. peer-to-peer car or ride sharing.
3. *Digitally-enabled transport modes*: Transport modes or transport mode operating models that would not exist without or largely rely on digital technologies. *Digital shared mobility services* could also be considered *digitally-enabled transport modes*. However, we created a separate category for these applications due to the unique services they provide to travelers.
4. *Digital in-vehicle applications*: Digital applications that are installed in vehicles and that improve performance characteristics of transport modes such as safety, fuel efficiency, convenience or travel time.
5. *Digital traffic and infrastructure management applications*: Digital applications that support the management of the transport system in order to increase efficiency and safety of (passenger) transport.

Digital in-vehicle applications support *digital traffic and infrastructure management* and *digital shared mobility services*, e.g. GPS sensors in connected cars can be used to track the vehicle location for traffic monitoring or ride sharing. *Digital traffic and infrastructure management* applications support *digital traveler information systems*, e.g. a public transport monitoring system can also be used to inform travelers about bus delays in real-time. *Digital traveler information systems* can integrate *digital shared mobility services*, e.g. a trip planner can also provide information on available ride or car sharing services. *Digital in-vehicle applications* and *digital traffic and infrastructure management* also support *digitally-enabled transport modes*, e.g. automated driving systems enable robotaxis.

Figure 2 provides a conceptual overview of digital applications in passenger transport. Please note that overlaps among application categories, various further representations and ways to cluster digital applications in passenger transport exist.

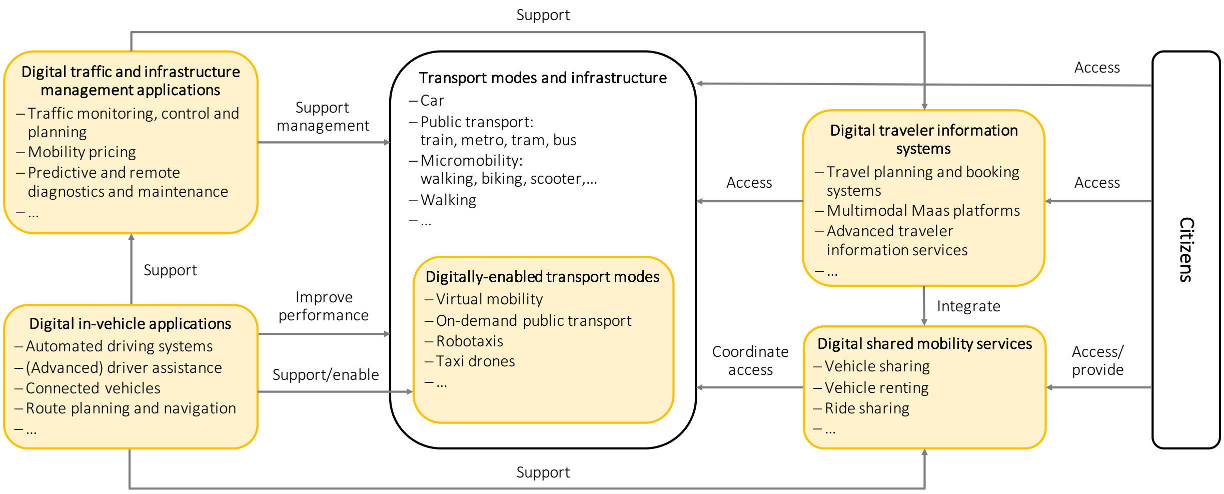

Figure 2: Conceptual overview of digital applications (in orange) by their impact on transport modes and infrastructures (e.g. improving the performance or the management of transport modes) and the functionality they provide to citizens (e.g. providing information on schedules or access to vehicles without ownership).

5.1 Digital traveler information systems

In the following, we describe digital information systems that support travelers in trip planning and booking.

5.1.1 Travel planning and booking systems

Travel planners provide information on routes, schedules and travel times for specific transport modes. Many travel planners also provide information on fares, the possibility to book and pay for tickets directly in the systems (Borkowski, 2017). For example, the website or app of the Swedish railway company SJ provides the possibility to find train routes and schedules in Sweden and other countries, to book tickets and to reserve seats. Kramers (2014) provides an overview of functionalities in such systems that can encourage travelers to take decisions that reduce transport energy use.

5.1.2 (Multimodal) MaaS platforms

Various definitions for MaaS exist, most of which describe mobility services that focus on meeting mobility needs of travelers, offer (multimodal) mobility rather than transport, and integrate several transport services (e.g. public transport, car or ride sharing) into one integrated service (Sochor et al., 2018). The integration of several transport services is usually supported by digital platforms that can be accessed through a digital interface, e.g. a smartphone app (Sochor et al., 2018). Sochor et al. (2018) propose a topology that distinguishes MaaS services by the degree of integration (Table 2).

Level	Title	Description	Example services
0	No integration	Every transport service is offered separately	Car rental services
1	Integration of information	Travelers can plan trips using single or a combination of transport services	Google Maps
2	Integration of booking and payment	Travelers can plan, book and pay for single trips using single or a combination of transport services	Jelbi, Move
3	Integration of the service offer	Travelers can meet their (entire) mobility needs with an integrated service that includes bundles of mobility services and possibly subscriptions	Whim, SBB Green Class
4	Integration of societal goals	Mobility services are integrated with societal goals, e.g. through policies and incentives to reduce car ownership and use.	n/a

Table 2: MaaS topology by degree of integration (Sochor et al., 2018).

5.1.3 Advanced traveler information systems

Advanced traveler information systems (ATIS) support “travelers with planning, perception, analysis and decision-making to improve convenience, transportation means and infrastructure” (Kem et al., 2017, p. 635). While an ATIS may include functionalities of trip planners and MaaS platforms such as multimodal trip planning and booking, they also provide additional services such as real-time updates on incidents, disruptions or delays, weather warnings and other trip-related information. ATIS can provide information through digital channels such as websites or mobile apps, but also through other channels, e.g. displays embedded in bus stops showing arrival or departure times or variable-message signs on highways indicating the length of traffic jams (Kem et al., 2017).

5.2 Digital shared mobility services

The digital sharing economy is a resources allocation system that allows temporary access to resources and is enabled by digital platforms (Pouri & Hilty, 2021). In this chapter, we describe services that provide temporary access to vehicles (and drivers) without ownership through digital platforms. Public transport is also a form of shared mobility but not included here, because it existed already before the widespread penetration of digital technologies.

5.2.1 Vehicle sharing

Vehicle sharing describes a system in which an entity temporarily uses a vehicle that is owned by another entity (Ataç et al., 2021). Today, common vehicle sharing services are car sharing, (e-)bike sharing, (e-)moped sharing and e-scooter sharing (Ataç et al., 2021). The shared vehicle is either owned by a company (business-to-consumer vehicle sharing) or by a private person (peer-to-peer vehicle sharing, Mutzel et al., 2018).

Vehicle sharing systems can be station-based (pick-up and drop-off of vehicles only at specific stations) or free-floating (pick-up and drop-off of at many places in a specific zone, Atal et al., 2021). Remain et al. (2016) provide an overview of further characteristics of car sharing services and business models. Vehicle sharing is often based on localization sensors in vehicles and on smartphones, that allow to find, book, pay for and open vehicles nearby. Geofencing can be used to ensure that users do not park vehicles outside the service areas.

5.2.2 Ride sharing

Various forms of sharing rides exist and the terminology in this field is ambiguous. Ride hailing services are similar to taxi services that are facilitated by smartphone apps to match passengers with nearby drivers (Ryan, 2020). The main services provided My Taxi, Uber or Lyft are exemplary ride hailing services.

Ride sharing services are similar to ride hailing services; however, (parts of) the rides are shared among several passengers who travel in the same direction (Ryan, 2020). The service is supported by smartphone apps to connect passenger and drivers and by advanced algorithms to optimize routes. Some ride sharing services require users to walk short distances to pick-up or drop-off points. Exemplary services are Berlkönig in Berlin or UberPool in the USA. Ride sharing can also be considered a form of on-demand public transport (see 5.3.2).

Ride pooling is the conventional way of sharing rides with other travelers, e.g. with co-workers in order to share fuel cost. Drivers are private individuals who need to travel a certain way and allow others to join (Ryan, 2020). A typical carpool trip is the commute, but it can also be used for other types of trips. For example, through BlaBlaCar any traveler can post a trip and invite others to join. Digital platforms facilitate matching of travelers.

While these are the most common types of vehicle and ride sharing services, further, more specialized services exist such as shared cars that can be used by residents of specific buildings.

5.2.3 Vehicle renting

In contrast to vehicle sharing, conventional vehicle renting is characterized by less dynamic booking (booking in advance and not spontaneously), centralized pick-up and drop-off stations and a wider selection of cars for different purposes (Car-Sharing vs. Car Rental, 2018). Vehicle renting can also be done for various types of vehicles such as cars, trucks and vans, (e-)bikes or mopeds. Conventionally, vehicles are rented for short periods (e.g. days or weeks). Still, subscription-based vehicle rentals exist, which allow travelers to rent a vehicle for a longer period of time (e.g. Clyde, n.d.; Jonna AB, n.d.). Renting vehicles already existed before increasing adoption of digital technologies, but today is often managed through digital platforms, which facilitate price comparisons, bookings and payments.

5.3 Digitally-enabled transport modes

In this chapter, we describe transport modes or transport mode operating models that would not exist without or largely rely on digital technologies.

5.3.1 Virtual mobility

Virtual mobility describes the virtual participation in activities without the need for physical travel. Virtual mobility is mainly enabled by remote access to data and the ability to virtually interact with people through audio or video calls and conferences (Bieser & Hilty, 2018). Virtual mobility is applied in diverse sectors (Table 3).

Virtual communication and collaboration technology is continuously improved and its adoption increased significantly during the COVID-19 pandemic. In future, fast and low-latency telecommunication networks and new types of end user devices can enable new forms of virtual collaboration. For example virtual reality solutions can allow participants of a meeting to “immerse into a shared virtual location, working together on shared 3D objects beyond text documents” (Bieser, Salieri, et al., 2020, p. 37).

Sector	Example applications
E-work	- Video conferencing - Document sharing - Messengers - Webinars
E-health	- Remote consultation - Remote health monitoring - Remote surgeries
E-education	- Distance learning (e.g. e-learnings, MOOCs, webinars) - Blended learning
E-banking	- Online banking - Remote consultation
E-events	- Virtual events - Remote participation (e.g. in concerts)
E-government	- Digital identification - Online forms
E-manufacturing	- Remote maintenance - Remote surveillance - Virtual worker training
E-commerce	- Online shopping
E-leisure	- Virtual sport lessons

Table 3: Overview of exemplary virtual mobility applications by sector.

5.3.2 On-demand public transport

On-demand public transport (or demand-responsive public transport) describes public transport that adjusts schedules or routes dynamically to travel demand (Petterson, 2019). On-demand public transport is mostly used in bus transport; however initiatives to make trains demand responsive exist (Dodgshun, 2018). In a review of on-demand bus services, Peterson (2019) provides an overview of central characteristics of these services (Table 4).

Category	Options
Type of vehicles	Minibus, bus, with/without wheelchair access
Service type	Commercial service, subsidized service
Routing and scheduling	Free-floating in specific zone, fixed destination or origin, zone-to-zone
Pick-up/drop-off points	Door-to-door service, virtual stops (locations that are not marked on street level), physical stops (e.g. bus stops)
Operating hours	Around the clock, adjusted to specific demands (e.g. on weekends, at night)
Booking method	Website, SMS, smartphone app, phone call, searchable in public transport planner
Timing of booking	<1h in advance of trip, >1h in advance of trip, >1 day before the trip
Pricing	Dynamic (e.g. by distance, time, congestion level), fixed price
Payment method	Smartphone app/credit card, public transport smart card, on-board payment

Table 4: Characteristics of on-demand bus services (Petterson, 2019).

While on-demand buses exist since some decades, specifically to offer transport services in areas or at times with low demand, it was often considered “expensive and fails to deliver the expected benefits because of barriers such as inadequate technology, mismatches between services and geographical conditions, lack of knowledge about users and various kinds of institutional barriers” (Petterson, 2019, p. 5). Digital technologies provide the possibility to overcome some of these barriers. Specifically, mobile devices and apps, localization services and AI enable more flexible booking of trips, capturing of location of travelers and buses and dynamic adjustment of routes and schedules according to demand. Automated driving systems reduce the cost of providing bus services as no driver is required anymore and thus can increase convenience of on-demand public transport because more busses can be put on roads (Bieser, Salieri, et al., 2020).

On-demand public transport could be considered an improvement of conventional public transport. Still, we included it in the category “new transport modes” because it largely relies on (digital) ICT and has a substantially different operating model than conventional public transport.

5.3.3 Robotaxis

Robotaxis describes the use of self-driving vehicles for providing taxi services (Vosooghi et al., 2019). They can be offered in the form of conventional taxi, ride hailing or ride sharing services (see 5.2.2).

5.3.4 Taxi drones

A transport mode that relies largely on modern digital technologies are unmanned aerial vehicles (UAVs, or drones). Drones are aircrafts that can fly without pilots onboard and are either autonomous or remotely controlled. They are supported by telecommunication networks for data exchange between the aircraft and a ground control station, geospatial technologies for localization, routing and air space management, sensors for capturing data about the environment, automation and robotics technology for operating the aircraft (Lakshmi Narayanan & Ibe, 2015).

Although they are still in their infancy, first taxi drones are already tested and used. For example, the “Hang 184” drone can carry weights up to 100 kg and fly at speeds up to 63 mph (Khan et al., 2018). There is some hope that taxi drones can provide a loophole out of congestion problems in cities (Khan et al., 2018); however, its widespread use cannot be expected in near future due to legal, ethical, safety, social and technical challenges (Kellermann et al., 2020).

5.4 Digital in-vehicle applications

In this chapter, we describe exemplary digital in-vehicle applications that improve performance characteristics of transport modes. Many different terms in the field exist, which partly describe the same applications. For example, some advanced driver assistance systems can be considered a form of driving automation or a connected car application. In the following we point at existing overlaps.

5.4.1 Automated driving systems

Automated driving systems are the “hardware and software that are collectively capable of performing part or all of the [dynamic driving task] on a sustained basis” (SAE International, 2016, p. 3). Even though the recent public debate focuses mainly on automated driving systems for cars, the technology can also be applied to other transport modes.

Automated cars

Technologies required for automated cars are for example LiDAR, radar, sonar or camera components to capture information on the surroundings of vehicles, on-board computers, advanced algorithms and communication equipment to process and transmit the captured data (Gawron et al., 2018). Automated driving technology for cars can be distinguished by the degree of automation from “no driving automation” (level 0) to “full driving automation” (level 5, no driver required anymore, SAE International, 2016). Autonomous, self-driving or driverless cars are terms commonly used to describe vehicles with level 4 or 5 automated driving systems.

Automated public transport

Automated public transport describes the application of automated driving systems in public transport (Tirachini & Antoniou, 2020), e.g. for self-driving buses, trains, metros or trams. Advantages of automation in public transport are that it is safer, more fuel efficient and more cost efficient as no driver is required anymore (Tirachini & Antoniou, 2020).

Automation can also facilitate on-demand public transport, if automation makes it more affordable to put more (smaller) on-demand buses into service that dynamically adjust routes according to demand because no driver is required anymore (see 5.3.2). Automated driving technology can also decrease the cost of taxi services significantly as the driver's salary is a major cost driver of today's taxi services (Hörl et al., 2019).

5.4.2 (Advanced) driver assistance

Advanced driver assistance "are intelligent systems that reside inside the vehicle and assist the main driver in a variety of ways" (Kala, 2016). As many of them automate parts of the dynamic driving task (e.g. cruise control, parking), they can be considered level 1 or level 2 automated driving systems. Kala (2016) distinguishes two types of advanced driver assistance systems:

- Information-based assistance systems, e.g. dynamic re-routing or inattention alert systems measuring driver performance
- Manipulation-based assistance systems, e.g. safety alert and emergency stopping, adaptive cruise control, overtaking assessment and assist, automated parking systems

Many advanced driver assistance systems for cars, trucks and rail transport exist. However, even for micromobility or walking, assistance systems exist. For example, systems to track the location vehicles to identify thefts (harvested GmbH, n.d.) or to monitor performance characteristics and diagnose failures (Bosch, n.d.-b, n.d.-a) are available for e-bikes and e-scooters. Blind Square (n.d.) provides voice navigation instructions for (partially) blind people when walking and Google Maps provides information about wheelchair accessibility for public transport (Google, n.d.).

5.4.3 Connected vehicles

Most literature on connected vehicles focuses on connected cars. Coppola and Morison (2016, p. 46:4) review literature in this field and propose the following definition:

"A connected car is a vehicle…

- capable of accessing the Internet at any time, using either a built-in device or brought-in user devices;
- equipped with a set of modern applications and dynamic contextual functionalities, offering advanced infotainment features to the driver and passengers;
- capable of interacting with other smart devices on the road or in mechanical shops, leveraging vehicle-to-road infrastructure communication technologies;
- capable of interacting with other vehicles, leveraging vehicle-to-vehicle communication technologies."

They distinguish five categories of applications that are supported by connected cars (Table 5), which partly overlap with applications that are supported by automated driving or advanced driver assistance systems, shared mobility services, traffic and infrastructure management. Many of these applications also exist for other transport modes such as navigation systems or vehicle tracking for scooters.

Category	Applications
Traffic safety	- Driver fatigue, anger, and stress detection - Accident avoidance and assistance (e.g. lane keeping systems) - Night vision assistant and head-up display - Remote maintenance, vehicle tracking and stolen vehicle assistance
Infotainment	- Music streaming - Video streaming, games, and Internet browsing - In-car Wi-Fi networks - Social networks (e.g. vehicle social networks and voice chats with drivers in proximity)
Traffic efficiency	- Navigation, online route planning, street view - Traffic, weather, and road condition monitoring - Assisted driving and autonomous vehicles - Connected parking
Cost efficiency	- Driver behavior profiling for insurance - Algorithm-based vehicle pricing (e.g. when buying used cars) - Energy optimization (e.g. calibrating drivetrains and managing charging/discharging) - Contextual advertisement (e.g. audio messages when driving by stores) - Vehicle testing (e.g. sharing performance data with OEMs)
Convenience, interaction, and others	- Smart-home integration (e.g. to control lighting, heating before arriving home) - Integration with wearable devices (e.g. for driver health monitoring) - Car sharing - Hand-free controls (e.g. voice control) - Driver profiles (e.g. to configure car settings individually)

Table 5: Applications supported by connected cars based on Coppola and Morison (2016, p. 46:4).

5.4.4 Route planning and navigation

Various applications support route planning before departure and real-time navigation while traveling for various transport modes. In trucks, buses or cars, route planning and navigation devices are often embedded in the on-board system. For micromobility or walking real-time navigation services are usually accessed with smartphones (e.g. with the Google Maps app). Some software providers specialize in navigation for specific micromobility modes such as bikes (Bikemap GmbH, n.d.). Route planning and navigation is a requirement for self-driving vehicles and can be considered a driver assistance system and connected car application as well.

5.5 Digital traffic and infrastructure management

"[T]raffic management can be defined as the system controlling traffic" which can be enabled through signals and information and intends to increase efficiency and safety of (passenger) transport (Lubello & Bousse, 2019, p. 17/18). The term intelligent transport systems (ITS) is often used in this context and describes the systematic use of ICT in transport, for traffic and infrastructure management but also for other purposes such as vehicle control or traveler information systems (Sussman, 2005).

5.5.1 Traffic monitoring, control and planning

Traffic flow monitoring and control

Traffic flow monitoring systems aim to capture and provide information about traffic flows such as traffic volumes, directional flows or speeds (Clearview Intelligence, n.d.; Tian et al., 2011). These systems can, for example, be implemented with intrusive road sensors (e.g. magnetic loops or ultrasonic sensors), non-intrusive road sensors (e.g. video cameras, Tian et al., 2011) or with communication modules installed in vehicles (e.g. Wi-Fi or Bluetooth modules, Zheng et al., 2019). Today, data captured via mobile networks (movements of smartphones across mobile network cells) can be used for traffic monitoring (Teralytics, 2021).

Data captured with traffic flow monitoring systems support various applications such as transport planning, traffic incident detection (the detection of anomalies in traffic) or congestion management

(Han et al., 2020; Tian et al., 2011; Zheng et al., 2019). Deriving meaningful insights from data captured with traffic flow monitoring systems is supported by software algorithms such as machine learning or pattern recognition algorithms (Han et al., 2020). These insights can be used to intervene in traffic with the intention “to accommodate traffic in a safe and efficient way” (Hobbs & Jovanis, 2018, p. 1).

Exemplary techniques to dynamically control road traffic are (automated) traffic signaling at intersections, variable-message signs and in-vehicle safety warnings for drivers. Advanced systems can even align routing advice for drivers with traffic signals (Hobbs & Jovanis, 2018). In public transport, traffic monitoring and control systems can feed information into (advanced) traveler information systems (see 5.1.3) and thereby support the reduction of peak loads and more comfortable travel experiences (Hobbs & Jovanis, 2018). In rail transport, monitoring and control techniques can be used to monitor and coordinate location and speed of trains with the aim to increase reliability of rail transport and increase utilization of the rail network (e.g. by reducing distances between trains, Hobbs & Jovanis, 2018). A more recent development is the enforcement of stricter traffic rules in specific urban zones with geofencing. For example, in low-emission zones hybrid vehicles could automatically switch to electric drive when crossing a virtual fence (Arnesen et al., 2021).

Digital twins, virtual representations of real-world object or processes (VanDerHorn & Mahadevan, 2021), can provide a virtual representation of the current state of a transport system (Hämäläinen, 2020) and thereby support the identification of measures to optimize traffic flows in real-time, and allow travelers to receive information about delays.

Fleet management

Fleet management systems support fleet operators in optimizing their fleet “in order to serve the customers demand with the objective of cost efficiency” (Bielli et al., 2011, p. 4), e.g. by finding the right fleet size, optimizing vehicle routing or planning of vehicle overhauls (Bielli et al., 2011; Killeen et al., 2019). An early overview of fleet management technologies suggest that four digital technologies support fleet management: vehicle location systems, mobile communication systems for data exchange, on-board computers to monitor driver and vehicle characteristics, routing and dispatching software to find the most efficient routes with respect to time and cost (Cambridge Systematics et al., 1996).

Fleet management systems are often discussed in the context of logistic systems and their optimization (e.g. for just-in-time delivery); however, they are also relevant in passenger transport, e.g. for public transport service providers or vehicle sharing providers (Fan et al., 2008; Hernandez Medel et al., 2008). With increasing prevalence of driverless vehicles, the importance of fleet management software will increase due to the absence of drivers. Integration of fleet management systems across transport modes is important to facilitate convenient multimodal passenger transport (Hernandez Medel et al., 2008).

Traffic simulations

“Traffic simulation is a widely used method applied in the research on traffic modelling, planning and development of traffic networks and systems” (Azlan & Rohani, 2018, p. 1). Traffic simulations allow “to emulate the time variability of traffic phenomena [...] for capturing the complexity of traffic systems” (Barceló, 2010a, p. vii) and can be realized with digital twins (Hämäläinen, 2020). These systems are supported by data on the state of the transport system captured with traffic monitoring systems, high-performance computers and advanced software applications and algorithms (Barceló, 2010a) that allow to simulate hypothetical scenarios (e.g. a change in the road or public transport network, a new mobility pricing policy, changing traffic demand) in a virtual world to identify potential consequences for transport system.

Traffic simulation models can be distinguished into three types of models (Barceló, 2010b):

- Microscopic models: models of vehicles and their movements (e.g. car following models, lane changing models, Azlan & Rohani, 2018).
- Macroscopic models: aggregate models of traffic which regard "traffic flows as a particulate fluid process" (e.g. models of the relationship between traffic speeds, flows and densities, Barceló, 2010, p. 15).
- Mesoscopic models: combination of microscopic and macroscopic models (e.g. by aggregating several vehicles into "packages" or "platoons" that travel through the road network, Barceló, 2010).

5.5.2 Mobility pricing

(Dynamic) Road user charging

Road user charging describes systems that charge drivers for using roads (KonSULT, 2016b). Fees can be adjusted dynamically, e.g. according to congestion levels or by time of the day, in order to avoid congestion. Pricing can take the form of an area licensing scheme (license fee for driving in an area), cordon pricing (fee for entering a certain area) or a continuous charging scheme (pricing based on distance or time travelled, KonSULT, 2016).

Area licensing schemes or cordon pricing can be implemented with paper licenses (e.g. paper licenses bought yearly and attached to car windows) or with manual toll collection (e.g. cash payment at toll points). Digital technologies such as video cameras at toll points, automatic number plate recognition, dedicated short range communication between vehicle on-board units and toll stations can simplify implementation of road user charging (KonSULT, 2016b). Specifically, continuous charging schemes and dynamic road user charging (e.g. varying prices depending on the time of the day) can benefit from digital technologies, as they require regular bidirectional information exchange between drivers (need to be informed about current prices) and transport system operators (need to be informed about distances driven in specific areas). Geofencing can help to streamline continuous and dynamic road user charging enforcement processes (e.g. as shown by Arnesen et al., 2021) and allow to implement (continuous) road user charging at high granularities (e.g. distinguishing several tariff zones from each other).

Dynamic mobility pricing

The principle of dynamic road user charging can be applied to other transport modes as well, e.g. to public transport. For example, in Switzerland the adoption of dynamic mobility pricing is currently discussed for rail transport in order to reduce peak loads in trains during rush hours (FEDRO, 2021).

Integrated ticketing

"Integrated ticketing allows a passenger to transfer within or between different public transport modes using a single ticket for their entire journey". It provides benefits for travelers such as reduced boarding time, simplified tariff structures, and for transport service providers such as more throughput and less operating costs (KonSULT, 2016a, p. 1). Integrated ticketing requires integration of systems among participating transport service providers.

5.5.3 Predictive and remote diagnostics and maintenance

Predictive maintenance

Predictive maintenance describes maintenance that "foresees faults or failures in a deteriorating system in order to optimize maintenance efforts by means of evaluating state of the system mostly and/or, in a broader sense, by means of historical data of the system in hand" (Selcuk, 2017, p. 1670). It is specifically relevant in asset-intensive industries (Bukhsh & Stipanovic, 2020) and where reliability and reduction of downtimes is relevant, such as transport (Selcuk, 2017).

Predictive maintenance is often based on sensor technology, that measures and provides data about characteristics of objects, that can be analyzed with dedicated software tools and algorithms (Selcuk, 2017). In transportation, predictive maintenance can be applied to vehicles (e.g. for fleet management of buses, Killeen et al., 2019) or to infrastructure (e.g. for analyzing conditions of bridges, Hallberg, 2009).

Remote diagnostics and maintenance

Remote diagnostics and maintenance describes diagnostics and maintenance that does not require physical presence, but can be conducted remotely (You et al., 2005). Similar to predictive maintenance, remote diagnostics and maintenance is supported by (wireless) telecommunication networks and sensor technology that captures information about the condition of objects and its environment (e.g. machines). In transport, for example, data about vehicle performance can be collected remotely and used to identify potential failures and derive suitable maintenance measures (You et al., 2005). Connected cars can even download software upgrades remotely (Halder et al., 2019). Remote diagnostics and maintenance applications can be improved further in future with low-latency mobile networks (e.g. 5G) and smart glasses that allow maintenance workers to immerse into a virtual world, working on virtual machines (Bieser, Salieri, et al., 2020; Müller et al., 2019).

6 Potential impacts of digital applications on passenger transport GHG emissions

The GHG impacts of passenger transport depend significantly on (based on Sims et al., 2014):

- Total distances traveled per year (pkm_{total})
- Modal choice of passengers (pkm_{mode}/pkm_{total})
- GHG intensity (CO_2e/pkm) by transport mode, which depends on the GHG intensity of the vehicles (CO_2e/vkm, vehicle kilometer) and the utilization of vehicles or number of passengers on board

Passenger transport is also associated with indirect or embedded emissions that are caused by the construction and maintenance of transport vehicles and infrastructures (Bieser & Höjer, 2021).

To identify opportunities and risks of digital applications in passenger transport for climate protection, we identified levers through which digital applications can reduce or increase passenger transport GHG emissions, clustered by the three strategies of the “Avoid-Shift-Improve”-Approach (6.1) and by the application categories described in section 5 (6.2).

6.1 Overview of GHG reducing and increasing levers

Table 6 summarizes the main levers through which digital applications can lead to a reduction or an increase of GHG emissions, clustered by the three strategies for sustainable transport put forward in the “Avoid-Shift-Improve”-Approach.

Strategy	**GHG reducing levers**	**GHG increasing levers**
Avoid/ increase	- Reduction of total number of vehicles produced if people give up privately-owned vehicles (e.g. through vehicle sharing or MaaS platforms) - Reduction of physical transport (e.g. through video conferencing) - Reduction of pkm traveled (e.g. through navigation systems or intelligent traffic guidance) - Reduction of vkm traveled by increasing the utilization of transport modes (e.g. through ride sharing)	- Production of additional shared vehicles - Increase in pkm traveled if travel convenience increases and/or cost per pkm decrease - Increase in pkm traveled if underserved demographic groups get access to transport modes (e.g. children using self-driving vehicles) - Increase in vkm traveled if self-driving vehicles drive empty without drivers - Increase in vkm and pkm traveled if more efficient planning and operation of transport systems allows for more vehicles on roads (e.g. through congestion reduction)
Shift	- Increased (relative) attractiveness of and shift to more GHG-efficient transport modes (e.g. through MaaS platforms, automated on-call buses or congestion pricing in city centers) - Access and shift to more GHG-efficient transport modes (e.g. through e-bike sharing)	- Increased attractiveness of and shift to more GHG-intensive transport modes (e.g. through car sharing services integrated in MaaS platforms, self-driving cars or congestion reduction on roads) - Access and shift to more GHG-intensive transport modes (e.g. through car sharing or ride hailing)
Improve/ worsen	- Increase in fuel efficiency (e.g. through cruise control or traffic flow optimization)	- No lever identified

Table 6: Levers through which digital applications can lead to a GHG emission reduction or increase clustered by the three strategies of the “Avoid-Shift-Improve”-Approach for sustainable transport (United Nations, 2016). We could not find a lever that worsens the environmental performance (i.e. the GHG or fuel efficiency) of transport modes.

Please note, that further effects of digital applications in passenger transport on GHG emissions exist such as the GHG impacts of producing and operating the ICT hardware and software required for the applications (Itten et al., 2020; Jattke et al., 2020; Vaddadi et al., 2020). For example, producing and operating the hardware and software for automated driving systems (e.g. on-board computers, cameras) is associated with GHG emissions (Gawron et al., 2018). Also, various applications can impact demand for transport infrastructures and thus GHG emissions caused by its construction. For example, self-driving vehicles and car sharing can reduce demand for parking space or roads (Anderson et al., 2016; Pernestål Brenden et al., 2017). These effects are usually only observable in the long-term (Bieser & Höjer, 2021).

6.2 GHG reducing and increasing levers by application category

Table 7 summarizes GHG reducing and increasing levers of digital applications in passenger transport by the application categories described in section 5. It shows that applications in each category can have both reducing and increasing impacts on passenger transport GHG emissions, which are described in more detail in the following.

Application category	GHG reducing levers	GHG increasing levers
Digital traveler information systems	- Increased attractiveness of and shift to more GHG-efficient transport modes (e.g. through MaaS platforms) - Reduction of total number of vehicles produced if people give up privately-owned vehicles	- Increased attractiveness of and shift to more GHG-intensive transport modes (e.g. through car sharing services integrated in MaaS platforms) - Increase in pkm traveled if travel convenience increases
Digital shared mobility services	- Reduction of vkm traveled by increasing the utilization of transport modes (e.g. through ride sharing) - Access and shift to more GHG-efficient transport modes (e.g. through e-bike sharing) - Reduction of total number of vehicles produced if people give up privately-owned vehicles (e.g. through vehicle sharing)	- Access and shift to more GHG-intensive transport modes (e.g. through car sharing or ride hailing) - Production of additional shared vehicles - Increase in pkm traveled if travel convenience increases and/or cost per pkm decrease
Digitally-enabled transport modes	- Shift to more GHG-efficient transport modes (e.g. on-demand public transport instead of car) - Reduction of physical transport (e.g. video conference instead of motorized travel)	- Shift to more GHG-intensive transport modes (e.g. to robotaxis instead of trains) - Increase in pkm traveled if travel convenience increases and/or cost per pkm decrease
Digital in-vehicle applications	- Increase in fuel efficiency (e.g. through cruise control) - Reduction of travel distances (e.g. through navigation systems, parking spot finder) - Increased attractiveness of and shift to more GHG-efficient transport modes (e.g. automated on-call busses)	- Increased attractiveness of and shift to more GHG-intensive transport modes (e.g. through self-driving cars) - Increase in pkm traveled if travel convenience increases and/or cost per pkm decrease - Increase in pkm traveled if underserved demographic groups get access to transport modes (e.g. children using self-driving vehicles) - Increase in vkm traveled if self-driving vehicles drive empty without drivers
Digital traffic and infrastructure management	- Reduction of distance traveled or increase in fuel efficiency through more efficient planning and operation of transport systems (e.g. through traffic flow optimization or intelligent traffic guidance) - Shift to more GHG-efficient transport modes (e.g. through congestion pricing in city centers)	- Increased attractiveness of and shift to more GHG-intensive transport modes (e.g. through congestion reduction on roads) - Increase in pkm and vkm traveled if more efficient planning and operation of transport systems allows for more vehicles on roads (e.g. through congestion reduction) - Increase in pkm traveled if travel convenience increases and/or cost per pkm decrease

Table 7: GHG reducing and increasing levers of digital applications in passenger transport by application category.

Digital traveler information systems

Travel planning and booking systems and advanced traveler information systems improve convenience before and during traveling, and thus can increase the use of the respective transport modes. The GHG impacts depend on whether this replaces the use of more or less GHG intensive transport modes and/or leads to additional vkm traveled (Bieser & Höjer, 2021).

For the case of multimodal MaaS platforms, the main opportunity for reducing GHG emissions is that they provide convenient solutions to travel from door-to-door by combining several transport modes, which originally was only conveniently possible with privately-owned cars (Hörcher & Graham, 2020). They can thereby reduce GHG emission if the use and ownership of cars decreases. Still, GHG impacts depend on the transport modes included in the MaaS platform (e.g. public transport, bike sharing, car sharing, ride sharing), their use, and its impact on the use of other transport modes. MaaS platforms can also integrate mechanisms to induce people to choose more GHG-efficient transport modes, e.g. through visual nudges in apps (Weinmann et al., 2016) or pricing models that create incentives to use GHG-efficient transport modes such as monthly subscriptions or mobility budgets (Hörcher & Graham, 2020; Zijlstra & Vanoutrive, 2018). However, mobility subscriptions can also lead to overconsumption (Hörcher & Graham, 2020), e.g. an increase in total travel distances.

Digital shared mobility services

Main opportunities of vehicle sharing services for a GHG reduction are that it reduces the number of vehicles produced as travelers have access to vehicles without owning them (e.g. through car sharing) or that it leads to a shift to more GHG-efficient transport modes (e.g. e-scooters instead of cars). However, vehicle sharing can also lead to an increase in the number of vehicles produced and a shift to more GHG-intensive transport modes, e.g. if people travel with a shared car instead of public transport (Bieser, Hintemann, et al., 2020).

The main opportunity for a GHG reduction through ride sharing is that it increases the average utilization of transport modes and thereby reduces the number of vkm travelled. This can be specifically the case for services in which rides are shared among several passengers who travel in the same direction. If ride sharing services are sufficiently reliable and convenient, they may even reduce private vehicle ownership and GHG emissions associated with production of the vehicles. However, if the rides are not shared with other travelers and replace travel with less GHG-intensive transport modes (e.g. car-based ride hailing instead of public transport), GHG emissions can increase (Bieser, Hintemann, et al., 2020).

Finally, if sharing services reduce the total cost per pkm, travel distances can increase. For example, Stapleton et al. (2016) showed that fuel cost savings in car travel can lead to a rebound effect and increase the distance travelled.

Digitally-enabled transport modes

The GHG emissions caused by digitally-enabled transport mode vary significantly by the type of transport mode. Usually, accessing activities virtually (e.g. with video conferences) is more GHG-efficient than motorized travel, even if the GHG impacts of production and operating the ICT equipment (e.g. video conferencing system) required for virtual presence are considered (e.g. Warland & Hilty, 2016). Robotaxis can be expected to reduce GHG emissions per vkm travelled compared to conventional taxis because self-driving vehicles are usually more fuel efficient than conventionally-driven vehicles (Anderson et al., 2016). GHG emissions caused by on-demand public transport depend on the GHG-intensity of the vehicles used, the routes and associated vkm travelled. Taxi drones can be assumed to be more GHG-intensive than ground-based transport modes for short- to medium-distance trips (Kasliwal et al., 2019). Still, for each new transport mode, the GHG impacts depend on its adoption by travelers, its impact on the use of more and less GHG-intensive transport modes and total vkm travelled.

Digital in-vehicle applications

Various applications such as automated driving systems or (advanced) driver assistance systems can increase the fuel efficiency of the respective transport modes (e.g. through platooning or cruise control, Bieser et al., 2020) or reduce the distance traveled (e.g. through route planning or parking spot finders, GeSI & Accenture Strategy, 2015). A main risk is that these applications make traveling with GHG-intensive transport modes such as cars more attractive in terms of convenience, travel time or cost and thus increase their use (Anderson et al., 2016; Pernestål Brenden et al., 2017; Sjöman et al., 2020).

Self-driving cars can increase vkm travelled with cars, for example, because they can be used by people who are not able to steer conventional cars (e.g. children, elderly), because they reduce travel time cost as other activities can be done in parallel (e.g. sleeping while driving), or because vehicles drive around empty (Coroamă & Mattern, 2019; Pernestål Brenden et al., 2017). However, self-driving vehicles can also facilitate on-demand public transport (e.g. automated on-call buses) and thereby increase the attractiveness of public transport in terms of convenience and cost and reduce use of privately owned cars (Krail et al., 2019).

Digital traffic and infrastructure management

The main purpose of traffic and infrastructure management applications is to increase efficiency and safety of (passenger) transport (Lubello & Bousse, 2019). Efficiency increases can lead to a GHG reduction, e.g. by reducing congestion or increasing fuel efficiency through automated traffic light control according to traffic volumes. If traffic and infrastructure management applications make travel with specific transport modes more efficient and thereby make travel more convenient, cheaper and allow for more vehicles on roads (e.g. due to congestion reductions and fuels savings), they can lead to an increase in the use of this transport mode or of pkm (or vkm) overall. For example, Sjöman et al. (2020) argue that congestion and stressful situations on roads are main reasons why travelers choose not to take the car and that congestion reductions might thus increase the use of cars. Dynamic mobility pricing systems can incentivize travelers to switch to more GHG-efficient transport modes (e.g. congestion pricing in city centers for cars). Digitally-supported traffic planning (e.g. through computer simulations) can help in designing future transport in a way that promotes climate-friendly travel.

7 Discussion

In the following, we discuss the relationship between digital technologies and applications (7.1) and impacts of digital applications on GHG emissions (7.2).

7.1 The relationship between digital technologies and applications

In total, we identified nine categories of digital technologies that are used in and shape passenger transport. These technologies support digital traveler information systems, digital shared mobility services, digitally-enabled transport modes, digital in-vehicle applications, and digital traffic and infrastructure management.

Each application benefits from a combination of digital technologies. (Mobile) end user devices support the interaction of travelers with other actors in the transport system (e.g. for ride sharing) or with vehicles (e.g. for theft monitoring) and provide assistance before and during traveling (e.g. for route planning and navigation). Telecommunication networks support almost all applications by enabling data exchange among travelers, vehicles, drivers and operators. AI and big data supports specifically applications that require automation or the solution of optimization problems (e.g. for routing, traffic planning, or predictive maintenance). Geospatial technologies are essential when information about the location of places, vehicles or travelers and the routes between those is required (e.g. for locating shared vehicles or optimizing routes). Automation and robots are required for all applications that have automation at their core (e.g. automated driving systems, robotaxis, taxi drones) and can support further applications that benefit from partial automation (e.g. automated traffic control). Digital sensors are specifically relevant for capturing information about the surroundings of vehicles (for automation) and the conditions of vehicles and infrastructures (for driver assistance, diagnostics and traffic monitoring). Cloud computing and blockchain can support all applications (e.g. for real-time access to data and secure data transfer), however are not necessarily required as most applications can also be realized without these technologies.

Also, various applications could be realized without the use of digital technologies. For example, car pooling can be organized via black boards at employer offices and car sharing with a central storage for car keys. Still, the increasing penetration of digital technologies in passenger transport indicates that the technologies help in better coordinating and managing travelers, service providers, vehicles and infrastructures. For many applications, a high penetration in practice seems improbable without the capabilities (and conveniences) provided by digital technologies. In fact, we could identify some trends in passenger transport that are driven by digital applications and the technologies behind (Table 8).

Trends	Description	Example applications supporting trend
Automation	Increasing automation of vehicle control and management of transport systems	Self-driving cars, automated traffic signaling, dynamic mobility pricing
Flexibilization	Increasing flexibility in transport systems, e.g. with respect to availability, travel time and cost or access to transport services	On-demand public transport, car and ride sharing, dynamic mobility pricing
Virtualization	Participating virtually in activities instead of physically traveling to a location	Video conferencing, telecommuting, virtual conferences, remote participation in events
Integration	Integration of various transport modes into a multimodal transport system	Multimodal route planners, trip booking and payment platforms, multimodal mobility subscriptions
Better control	Better control of vehicles and transport infrastructure to optimize processes	Traffic monitoring and control, fleet management systems, low emission zones with geofencing, remote maintenance
Efficiency increase	Increasing efficiency of the transport system, e.g. with respect to travel time and cost, energy consumption and emissions	Automated driving, real-time navigation, traffic simulations, ride sharing
Decentralization	Reduction of dependency on large transport services providers	Peer-to-peer ride or car sharing, multimodal MaaS platforms

Table 8: Trends in passenger transport that are supported by digital applications and example applications supporting the trends.

7.2 Potential impacts of digital applications on passenger transport GHG emissions

We showed that all described digital applications can have both reducing and increasing effects on passenger transport GHG emissions. In order put digital applications in passenger transport at the service of climate protection, the applications and services should be designed in a way that they promote GHG reducing levers and prevent GHG increasing levers.

In a real-life setting, the impacts of a digital application on passenger transport and associated GHG emissions depend on various interacting factors such as the application or service design (e.g. the user interface or the pricing model), the policy context and (changes to) individual travel behaviors, which can be different for individuals with different demographic and socio-demographic backgrounds (Bieser & Höjer, 2021; Pawlak et al., 2015). For example, the adoption of a new car pooling platform and its impact on travel behaviors and GHG emissions depends on common commuting patterns of citizens, the home office policies, fuel taxes and road user chargers in place. Figure 3 illustrates the interactions among the transport system, citizens, the broader socio-economic system and policy framework, and the natural environment.

Thus, even though large theoretical climate protection potentials of digital applications in passenger transport exist, there is a lot of uncertainty about the exploitation of these potentials in a real-life setting. If digital applications are introduced with the aim of reducing passenger transport GHG emissions, the application should be designed in a way that it provides incentives for travelers to reduce travel or to choose (more) climate-friendly travel options within the existing policy framework; and/or the policy framework has to be adjusted in order to create those incentives. If not, there is a risk that digital applications that appear climate-friendly at first, turn out to increase passenger transport GHG emissions through a shift to more GHG-intensive transport modes, an increase in total travel distances or the number of vehicles produced. Such effects have been observed several times in the past, e.g. in the case of ride hailing services such as Uber (Tirachini, 2020) or e-scooter sharing systems (Moreau et al., 2020).

A central issue is that revenues of providers of digital applications in passenger transport are often coupled to the distance travelled with the transport modes offered through the applications. Thus, providers that strive to contribute to climate-friendly mobility face target conflicts, at least with regards to the "avoid" strategy for sustainable passenger transport.

In some cases, digital applications may not even provide the possibility to contribute to climate protection. For example, in a 15-minute city in which citizens access places mainly by foot or by bike, the potential of digital applications to reduce passenger transport GHG emissions by avoiding travel or shifting travel to more climate-friendly transport modes, or to improve the GHG-efficiency of transport modes is limited.

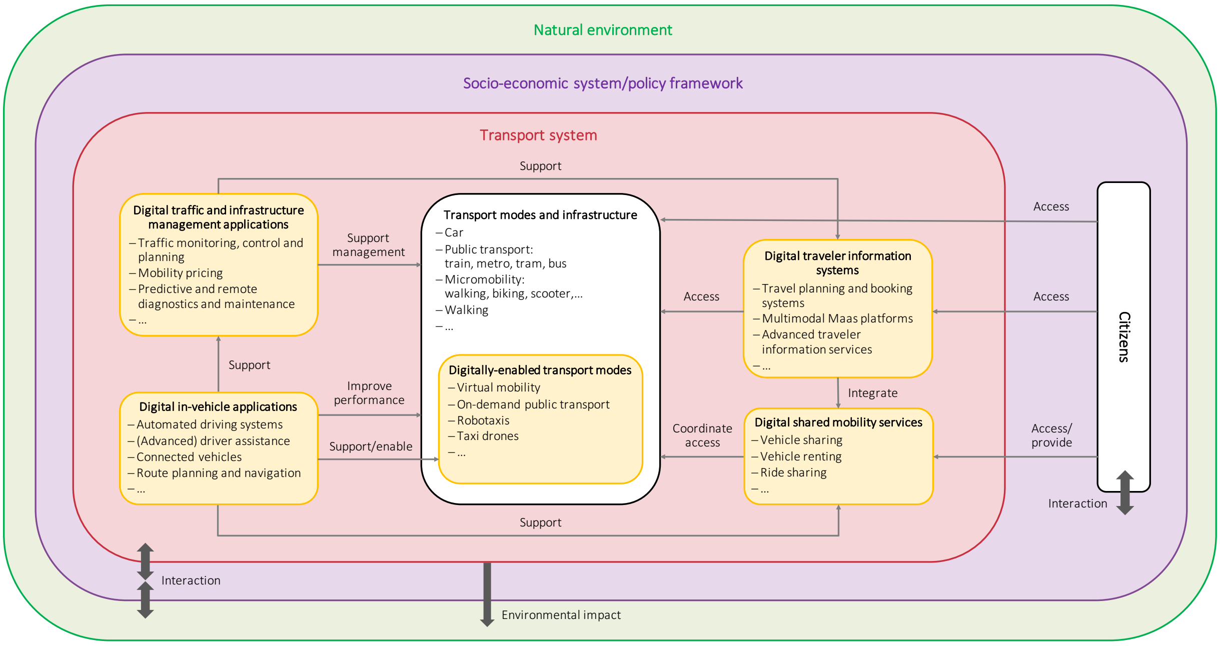

Figure 3: Conceptual illustration of interactions among the transport system, citizens, the broader socio-economic system and policy framework, and the natural environment.

8 Conclusion

In total, we identified nine main categories of digital technologies that are used in and shape passenger transport. These include (mobile) end user devices and apps, telecommunication networks, cloud computing, AI and big data, geospatial technologies, digital sensors, computer graphics, automation and robotics and blockchain. These technologies support various applications in passenger transport which can be categorized into digital traveler information systems, digital shared mobility services, digitally-enabled transport modes, digital in-vehicle applications and digital applications for traffic and infrastructure management. Still, digital technologies should be merely seen as "enablers" of digital applications in passenger transport and different ways to realize applications—even non-digital ones—exist.

Applications in all categories can have both reducing and increasing effects on GHG emissions from passenger transport. Main levers to reduce GHG emissions through digital applications are:

- Reduction of vehicle ownership and the number of vehicles produced (e.g. through vehicle sharing)
- Reduction of total travel distances (e.g. through virtual mobility or navigation systems)
- Increased attractiveness of and shift to more GHG-efficient transport modes (e.g. through MaaS platforms)
- Increase in the utilization of transport modes and reduction of vkm traveled (e.g. through ride sharing)
- Increase in the fuel efficiency of vehicles (e.g. through automated driving systems)

Whether or not digital applications in passenger transport contribute to climate protection depends on the interplay between the applications and their design, existing travel patterns and the policy framework in place. The application design and the policies in place have to be aligned and optimized together, not separately. Otherwise, there is a risk that digital applications lead to an increase in GHG emissions through a shift to more GHG-intensive transport modes, an increase in total travel distances or the number of vehicles produced—effects that have been observed in the past, in the case of ride hailing or e-scooter sharing services. This calls for coordinated action of policy makers and market actors to create conditions under which offering digital applications in passenger transport contributes to a net GHG emission reduction and is economically-feasible.

Future research should empirically assess the impacts of digital applications on passenger transport in a real-life setting and derive the application and policy design measures required to create climate-friendly digital passenger transport. We hope this report provides a foundation for such work and for putting the digitalization of passenger transport at the service of climate protection.

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Appendix

A. Description of digital technologies

(Mobile) End user devices and apps

End user devices such as desktop computers, laptops or tablets provide users the possibility to *display (actuate), process and transmit* data. Mobile end user devices such as smartphones or tablets can be used on-the-go and usually transmit data via mobile telecommunication networks. They are often also equipped with *sensors* (Anjum & Ilyas, 2013), e.g. GPS sensors, cameras, gyroscopes, to capture data about the physical environment of the device which can be used by software applications.

The computational power of devices is continuously increasing and so are the number and types of software applications (e.g. mobile apps) that can be run on these devices. For example, the processor used for the iPhone 7 had clock rate of 2.34 GHz and 3.28 bn transistors, whereas the iPhone 12 processor had a clock rate of 3.1 GHz and 11.8 bn transistors (Apple Wiki, 2021). The number of apps offered through Apple's App Store increased from roughly 50'000 in 2008 to roughly 3'400'000 in 2020 (Statista Research Department, 2021b).

Telecommunication networks

A communication network is "a group of devices connected to one another" and can be used to *transmit* data among devices (Grigorik, 2013, p. 80). Telecommunication networks can be distinguished in fixed and wireless networks. Fixed networks usually utilize copper and fiber-optic glass cables to transport data. Even though copper lines can support high-speed data traffic, their capacity is limited. Thus, network operators increasingly replace copper with fiber-optic transmission lines to increase capacity and speed while reducing latency (OECD, 2015). Wireless networks can be distinguished according to their geographic range (Table 9).

Wireless network type	**Range**	**Example technologies**
Personal area networks	Within the reach of a person	Bluetooth, ZigBee, NFC
Local area networks	Within a building or campus	Wi-Fi
Metropolitan area networks	Within a city	WiMAX
Wide area networks	Worldwide	Cellular (e.g. UMTS, LTE)

Table 9: Wireless network types, their range and example technologies (Grigorik, 2013).

End-user devices are equipped with diverse wireless network technologies such as Bluetooth and Wi-Fi. Mobile phones are also equipped with cellular network technologies, which are often referred to as mobile network technologies. Table 10 provides an overview of the first four generations of cellular network technologies including their data rates (the amount of data which can be send via a network per unit of time) and latency (the time a data packet requires for travelling from the sender to the receiver). Currently the fifth generation of cellular networks (5G) is being rolled out. It is the first generation of cellular networks which provides data rates that can compete with fixed networks. In addition, it provides further capabilities such as ultra-low latency, high reliability and the possibility to connect many devices (ITU, 2017).

Cellular network generation	**Launch/ release**	**Description**	**Data rate**	**Latency**
1G	1979	Analogue system for voice transmission	Voice only	
2G	1991	First digital system including data transmission (e.g. for text messaging, SMS) and mobile Internet access (for text-based websites)	100-400 Kbit/s	300-1'000 ms
3G	1999	First broadband Internet allowing for multimedia websites and audio and video streaming.	0.5-5 Mbit/s	100-500 ms
4G	2008-2011	Fast broadband Internet allowing, for example allowing for HD audio and video streaming.	1-50 Mbit/s	<100 ms

Table 10: Evolution of mobile network generations (Bieser, Salieri, et al., 2020) based on (Grigorik, 2013).

The Internet is a special type of communication network that uses the TCP/IP protocol to connect devices (Abbate, 2017) and that can be accessed via fixed and wireless networks. The Internet of Things (IoT) describes the phenomenon that not only people transmit data amongst each other (e.g. via computers or smartphones), but that objects are equipped with connectivity and exchange data amongst each other (Dorsemaine et al., 2015), e.g. smart light bulbs and heaters in a smart home, machines in manufacturing, connected cars. In many IoT applications, data-exchanging devices are distributed on large areas and not connected to a fixed electricity supply such as sensors on agricultural fields to measure soil conditions. So-called low power wide area networks (LPWAN, e.g. Sigfox, LoRa, LTE-M, Narrowband IoT) are designed to enable exchange of smaller data volumes over a wide range at low energy consumption (Bieser, Salieri, et al., 2020).

Cloud computing

Cloud computing describes the provisioning of ICT services (e.g. processing power, storage, software applications) in centralized data centers that can be accessed over the Internet (Repschläger et al., 2010). This means that data *processing* or *storage* no longer takes place on local user devices (servers, computers, smartphones; user can be companies or end users), but in the data centers of the cloud computing service provider. The users then access the computing resources or application through an interface environment, e.g. through a web browser, on their device.

Cloud computing services can be distinguished into three main categories (Repschläger et al., 2010):

- Infrastructure as a Service, IaaS: provisioning of computing resources such as storage or processing power in the cloud.
- Platform as a Service, PaaS: provisioning of computing resources including a developing environment in the cloud
- Software as a Service, SaaS: provisioning of software applications that are accessed by users in the cloud.

A main advantage of cloud computing is that it provides access to high-performance computing resources that allow for computations that would not be possible on local devices. For applications run on mobile devices whose storage and battery capacity is limited, it can be an advantages to provide these as cloud services (SaaS) to minimize local storage of data (e.g. detailed maps of the whole word) and energy consumption (Fernando et al., 2013). For companies, cloud computing enables fast up- and downscaling of ICT resources according to an organization's requirements (Repschläger et al., 2010). Cloud computing also provides an advantage when multiple parties need to share, access or process the same data, often in real-time. This can include document sharing solutions (e.g. DropBox) or online collaboration tools (e.g. Google Docs) that support remote work, or vehicle and ride sharing solutions which require sharing and matching of locations of travelers, vehicles and drivers.

Artificial intelligence and big data

Various terms in this field exist including AI, machine learning, advanced analytics, and big data, all of which support the analysis *(processing)* of large amounts of data to derive meaningful insights that could not have been derived with traditional data analysis techniques and smaller data volumes. These insights can for example be used for predictions (e.g. of travel demand), to solve optimization problems (e.g. calculation optimal routes for a demand-responsive bus system) or to automate human decision making (e.g. in self-driving vehicles). In the following, we present one way of conceptualizing important concepts in this field.

In its broadest sense, AI can be defined as "the ability of computers to perform complex tasks and exhibit human-like intelligence […]. The concept of AI by itself does not specify which exact technology is used, but rather refers to the complexity of the intellectual task that is now performed automatically" (Samuylova, 2019, p. 1).

Advanced analytics is "the autonomous or semi-autonomous examination of data or content using sophisticated techniques and tools […] to discover deeper insights, make predictions, or generate recommendations" such as data/text mining or semantic analysis (Gartner, n.d., p. 1). Machine learning "algorithms use large sets of data inputs and outputs to recognize patterns and effectively "learn" in order to train the machine to make autonomous recommendations or decisions" (Helm et al., 2020, p. 69). Thus, machine learning is a form of advanced analytics that focuses on the "learning ability of algorithms" through pattern recognition.

Big data describes large volumes of data from various sources that increase at a fast pace. Big data is used as an input for machine learning, advanced analytics or AI in general (Chandra, 2019).

Geospatial technologies

"Geospatial technologies is a term used to describe the range of modern tools contributing to the geographic mapping and analysis of the Earth and human societies" (AAAS, 2021, p. 1). In transport, geospatial technologies provide the possibility to *sense*, *process*, *transmit* and visualize geospatial data. For example, satellite systems or telecommunication networks can be used to track the (real-time) location of people and objects, digital maps can be used to visualize locations, and routing algorithms to calculate the shortest path between two places. Graphical information systems (GIS) is a domain of geospatial technologies that uses computers for the handling of geospatial data (AAAS, 2021).

A geospatial technology that is intensively discussed in recent years is geofencing. "Geofences are virtual geographic boundaries that enable software and applications to trigger a response when mobile devices enter or leave a particular area" (Dabbs, 2018). For example, geofencing can be used to ensure that vehicles automatically adjust the speed when they enter low-speed or low-emission zones (Arnesen et al., 2021) or that vehicles owned by sharing service providers (e.g. cars or e-scooters) cannot be parked outside the service area.

Digital sensors

"A *sensor* is a device [...] that detects events or changes in its physical environment (e.g., temperature, sound, heat, pressure, flow, magnetism, motion, and chemical and biochemical parameters) and provides a corresponding output" (Rayes & Salam, 2017, p. 58). While analogue sensors produce a continuous output signal, digital sensors convert analogue to digital (discrete) output signals (Rayes & Salam, 2017; Thomas et al., 2015). Smart sensors are equipped with further components such as microprocessors and communication components that allow to trigger a reaction (e.g. send data) only when specific conditions are met (Rayes & Salam, 2017). Table 11 provides an overview of selected sensors classified by the phenomenon they sense.

Phenomenon	Description	Example application
Proximity	Detecting the position of objects nearby	Parking assist system
Position	Detecting the position of objects or people in a particular area	Navigation system
Occupancy	Detecting the presence of humans or objects in an area	Building automation
Motion	Detecting the physical movement of objects in the environment	Home security systems
Velocity	Detecting the rate of change in the position (speed, rotation)	Speed control systems
Pressure	Detecting the amount of force	Tire pressure sensors
Image	Detecting light to convey images	Digital cameras
Temperature	Detecting heat energy	Overheat protections
Humidity	Detecting moisture in the environment	Climate monitoring

Table 11: Types of sensors classified by the phenomenon they sense and example applications (based on Sehrawat & Gill, 2019).

Continuous improvements of sensor performance with respect to size, cost, power consumption, weight or accuracy (Fitzgerald et al., 2018; Guerrero-Ibáñez et al., 2018; Smart Sense, 2020) have led to an increasing penetration of sensors in diverse infrastructures such as buildings, streets or electricity grids. In the IoT sensors are used to capture data about the physical environment of objects that can be transmitted over telecommunication networks. For example, soil sensors in agricultural fields can be used to monitor the humidity of soils in order to identify the optimal time and duration of irrigation. Sensors thereby “bridge the world’s physical objects with the Internet” (Rayes & Salam, 2017, p. 59).

Sensors in road transport can be clustered into in-vehicle sensors (e.g. for tire pressure sensors for vehicle diagnostics or radars for driver assistance), intrusive road sensors (e.g. magnetic sensors in pavements to count vehicles or the utilization of parking spots), and non-intrusive sensors (e.g. cameras on masts to monitor traffic volumes, Guerrero-Ibáñez et al., 2018). Mobile devices are also equipped with sensors (e.g. gyroscopes, cameras) that capture information about the device and its owner. Geospatial technologies are also using sensors (e.g. GPS sensors) to capture information about the location of objects and people.

Computer graphics

Computer graphics are “methods and techniques for converting data to and from a graphic display via computer[s]” (Enderle et al., 1987, p. 2). It deals with creating visual representations out of formal descriptions (e.g. data), creating formal description out of visual representations and the *processing* of visual representations (e.g. images processing, Enderle et al., 1987). Computer graphics uses hardware such as monitors and graphic cards to transform data into optically visible signals (*actuating*, Enderle et al., 1987). One of the main benefits of computer graphics is that “visually presented information can be accessed by human perception [...] in less time, in greater number, and with fewer errors than in any other way” (Enderle et al., 1987, p. 2f.).

Computer graphics are applied in transport whenever computer-generated visualizations are used, for example: transport vehicles are developed with computer aided design (CAD) tools (Hirz et al., 2017), transport systems are optimized with visual representations of traffic flows (Kornhauser, 1987), video conferences enable face-to-face conversations without physical presence, head-up displays provide information on windshields without requiring the driver to look away from the driveway (Zhu & Zhang, 2020). Computer vision is a related field that helps in automatically identifying objects in images and supports automated driving systems (Janai et al., 2020).

Automation and robots

Automation can be defined as “the process of following a predetermined sequence of operations with little or no human labour” (Gupta & Arora, 2009, pp. 1-2). A robot can be defined as “an autonomous machine capable of sensing its environment, carrying out computations to make decisions, and performing actions in the real world” (*sensing*, *processing*, *actuating*, Guizzo, 2018, p. 1,). Robots are sometimes considered the most advanced or most visual form of automation (Ceccarelli, 2004; Gupta & Arora, 2009). Often, robots exchange data (*transmission*) with surrounding robots or a central unit which submits instructions (e.g. the next pick-up location for a delivery).

Significant progress has been made in driving automation systems in recent years. A driving automation system is the “hardware and software that are collectively capable of performing part or all of the [dynamic driving task] on a sustained basis” (SAE International, 2016, p. 3). This technology can be used to automate conventional vehicles such as cars or to develop new types of vehicles such as unmanned aerial vehicles (drones) or delivery robots (Hoffmann & Prause, 2018; Stevens & Atkins, 2018). Automation and robots also penetrates other domains of the transport sector such as automated traffic monitoring and control systems (e.g. automatic adjustment of traffic lights according to traffic volume monitored with sensors) or manufacturing processes of automakers (Brogårdh, 2007; Talukder et al., 2017).

Blockchain

A blockchain is a decentralized database that is mirrored in the network on a variety of computers. Entries (e.g. transactions) are summarized and *stored* in blocks. A consensus mechanism (*process*) used by all computers ensures the authenticity of database entries (Mitschele, n.d.). Smart contracts are based on blockchain technology and "permit trusted transactions and agreements to be carried out among disparate, anonymous parties without the need for a central authority, legal system, or external enforcement mechanism" (Frankenfield, 2021, p. 1).

A major benefit of the blockchain is that it reduces transaction costs, can facilitate transactions among parties which do not trust each other and reduces dependency on a central (trusted) entity (e.g. banks, Frankenfield, 2021; Mitschele, n.d.). Thus, "Blockchain technology encourages the building of ecosystems with many participants, who share similar interests but don't trust each other because of the competition in the market" (Gösele & Sandner, 2018, p. 15).

Gösele and Sandner (2018) analyze the suitability of using the blockchain in diverse mobility applications such as car-wallets that allow cars to make payments on their own (e.g. for toll payments on roads) or vehicle black boxes to capture data about the usage and history of cars. Blockchain can also support decentralization of mobility services by facilitating direct secure and private data exchange among travelers and small mobility service provider (e.g. drivers, P2P car sharers) and avoid the need for a central service provider (Nguyen et al., 2019).

References

AAAS. (2021). *What are geospatial technologies?* American Association for the Advancement of Science. https://www.aaas.org/programs/scientific-responsibility-human-rights-law/overview-geospatial-project

Abbate, J. (2017). What and where is the Internet? (Re)defining Internet histories. *Internet Histories*, *1*(1–2), 8–14. https://doi.org/10.1080/24701475.2017.1305836

Amatuni, L., Ottelin, J., Steubing, B., & Mogollón, J. M. (2020). Does car sharing reduce greenhouse gas emissions? Assessing the modal shift and lifetime shift rebound effects from a life cycle perspective. *Journal of Cleaner Production*, *266*, 121869. https://doi.org/10.1016/j.jclepro.2020.121869

Anderson, J. M., Kalra, N., Stanley, K. D., Sorensen, P., Samaras, C., & Oluwatola, T. A. (2016). *Autonomous Vehicle Technology: A Guide for Policymakers*. Rand Corporation. https://www.rand.org/pubs/research_reports/RR443-2.html

Anjum, A., & Ilyas, M. U. (2013). Activity recognition using smartphone sensors. *2013 IEEE 10th Consumer Communications and Networking Conference (CCNC)*, 914–919. https://doi.org/10.1109/CCNC.2013.6488584

Apple Wiki. (2021). *List of Apple processors*. https://apple.fandom.com/wiki/List_of_Apple_processors

Arnesen, P., Seter, H., Tveit, Ø., & Bjerke, M. M. (2021). Geofencing to Enable Differentiated Road User Charging. *Transportation Research Record*, 0361198121995510. https://doi.org/10.1177/0361198121995510

Ataç, S., Obrenović, N., & Bierlaire, M. (2021). Vehicle sharing systems: A review and a holistic management framework. *EURO Journal on Transportation and Logistics*, *10*, 100033. https://doi.org/10.1016/j.ejtl.2021.100033

Azlan, N. N. N., & Rohani, M. M. (2018). Overview Of Application Of Traffic Simulation Model. *MATEC Web of Conferences*, *150*, 03006. https://doi.org/10.1051/matecconf/201815003006

Banta, D. (2009). What is technology assessment? *International Journal of Technology Assessment in Health Care*, *25*(S1), 7–9. https://doi.org/10.1017/S0266462309090333

Barceló, J. (2010a). *Fundamentals of Traffic Simulation* (1st ed.). Springer. https://link.springer.com/book/10.1007/978-1-4419-6142-6#about

Barceló, J. (2010b). Models, Traffic Models, Simulation, and Traffic Simulation. In J. Barceló (Ed.), *Fundamentals of Traffic Simulation* (pp. 1–62). Springer. https://doi.org/10.1007/978-1-4419-6142-6_1

Bielli, M., Bielli, A., & Rossi, R. (2011). Trends in Models and Algorithms for Fleet Management. *Procedia - Social and Behavioral Sciences*, *20*, 4–18. https://doi.org/10.1016/j.sbspro.2011.08.004

Bieser, J. C. T. (2020). A time-use approach to assess indirect environmental effects of information and communication technology: Time rebound effects of telecommuting. Dissertation, *University of Zurich*. https://doi.org/10.5167/uzh-191486

Bieser, J. C. T., & Coroamă, V. C. (2021). Direkte und indirekte Umwelteffekte der Informations- und Kommunikationstechnologie. *Sustainability Management Forum | NachhaltigkeitsManagementForum*, *29*(1), 1–11. https://doi.org/10.1007/s00550-020-00502-4

Bieser, J. C. T., & Hilty, L. (2018). Assessing Indirect Environmental Effects of Information and Communication Technology (ICT): A Systematic Literature Review. *Sustainability*, *10*(8), 2662. https://doi.org/10.3390/su10082662

Bieser, J. C. T., Hintemann, R., Beucker, S., Schramm, S., & Hilty, L. (2020). *Klimaschutz durch digitale Technologien: Chancen und Risiken*. Bitkom, Boderstep Institute for Innovation and Sustainability, University of Zurich. https://www.bitkom.org/sites/default/files/2020-05/2020-05_bitkom_klimastudie_digitalisierung.pdf

Bieser, J. C. T., Salieri, B., Hischier, R., & Hilty, L. (2020). *Next generation mobile networks: Problem or opportunity for climate protection?* University of Zurich, Empa, Swisscom, Swisscleantech. https://www.zora.uzh.ch/id/eprint/191299/

Bieser, J. C. T., & Höjer, M. (2021). *A Framework for Assessing Impacts of Information and Communication Technology on Passenger Transport and Greenhouse Gas Emissions*. 35th International Conference on Informatics for Environmental Protection (EnviroInfo 2021), Berlin. Accepted for publication

Bieser, J. C. T., Vaddadi, B., Kramers, A., Höjer, M., & Hilty, L. M. (2021). Impacts of telecommuting on time use and travel: A case study of a neighborhood telecommuting center in Stockholm. *Travel Behaviour and Society*, *23*, 157–165. https://doi.org/10.1016/j.tbs.2020.12.001

Bikemap GmbH. (n.d.). *Bikemap*. Retrieved June 10, 2021, from https://www.bikemap.net/de/

BlindSquare. (n.d.). *BlindSquare*. Retrieved June 10, 2021, from https://www.blindsquare.com/de/

Borkowski, P. (2017). Towards an Optimal Multimodal Travel Planner—Lessons from the European Experience. In G. Sierpiński (Ed.), *Intelligent Transport Systems and Travel Behaviour* (pp. 163–174). Springer International Publishing. https://doi.org/10.1007/978-3-319-43991-4_14

Bosch. (n.d.-a). *Connected eBiking*. Bosch. Retrieved June 10, 2021, from https://www.bosch-ebike.com/en/connect/

Bosch. (n.d.-b). *Smart vernetzt – mit COBI.Bike*. Bosch. Retrieved June 10, 2021, from https://www.bosch-ebike.com/de/produkte/cobibike/

Brennen, S., & Kreiss, D. (2014). *Digitalization and Digitization*. Culture Digitally. http://culturedigitally.org/2014/09/digitalization-and-digitization/

Brogårdh, T. (2007). Present and future robot control development—An industrial perspective. *Annual Reviews in Control*, *31*(1), 69–79. https://doi.org/10.1016/j.arcontrol.2007.01.002

Bukhsh, Z. A., & Stipanovic, I. (2020). Predictive Maintenance for Infrastructure Asset Management. *IT Professional*, *22*(5), 40–45. https://doi.org/10.1109/MITP.2020.2975736

Cambridge Systematics, ATA Foundation, & Systematics. (1996). *Commercial Vehicle Fleet Management and Information Systems* (ITS Fleet Management Technology Resource Guide Technical Memorandum 3). US Department of Transportation. https://rosap.ntl.bts.gov/view/dot/3812

Car-Sharing vs. Car Rental. (2018). CarClub. https://www.carclub.com.sg/car-sharing-rental-difference/

Ceccarelli, M. (2004). Introduction to Automation and Robotics. In M. Ceccarelli (Ed.), *Fundamentals of Mechanics of Robotic Manipulation* (pp. 1–28). Springer Netherlands. https://doi.org/10.1007/978-1-4020-2110-7_1

Chandra, H. (2019). *Artificial Intelligence (AI) vs Machine Learning (ML) vs Big Data*. Heartbeat. https://heartbeat.fritz.ai/artificial-intelligence-ai-vs-machine-learning-ml-vs-big-data-909906eb6a92

Clearview Intelligence. (n.d.). *Traffic flow monitoring*. Clearview Intelligence. Retrieved June 10, 2021, from https://www.clearview-intelligence.com/solutions/network-management/traffic-flow-monitoring-system

Clyde. (n.d.). *Clyde*. Retrieved June 10, 2021, from https://clyde.ch/en

Coppola, R., & Morisio, M. (2016). Connected Car: Technologies, Issues, Future Trends. *ACM Computing Surveys*, *49*(3), 46:1-46:36. https://doi.org/10.1145/2971482

Coroamă, V., & Mattern, F. (2019). Digital Rebound—Why Digitalization Will not Redeem us our Environmental Sins. *ICT4S2019. 6th International Conference on Information and Communication Technology for Sustainability*, *2382*. http://ceur-ws.org/Vol-2382/

Couclelis, H. (2000). From Sustainable Transportation to Sustainable Accessibility: Can We Avoid a New Tragedy of the Commons? In *Information, Place, and Cyberspace* (pp. 341–356). Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-662-04027-0_20

Dabbs, M. (2018). A Beginner's Guide to Geofencing Apps for Mobile. *Reinvently*. https://reinvently.com/blog/geofencing-apps-for-business/

Dodgshun, J. (2018). The race for rail-on-demand. *Technologist*. https://www.technologist.eu/the-race-for-rail-on-demand/

Dorsemaine, B., Gaulier, J.-P., Wary, J.-P., Kheir, N., & Urien, P. (2015). Internet of Things: A Definition & Taxonomy. *2015 9th International Conference on Next Generation Mobile Applications, Services and Technologies*, 72–77. https://doi.org/10.1109/NGMAST.2015.71

Enderle, G., Kansy, K., & Pfaff, G. (1987). *Computer Graphics Programming: GKS — The Graphics Standard* (2nd ed.). Springer-Verlag. https://doi.org/10.1007/978-3-642-71079-7

European Comission. (2020). *Technical support related to sustainable urban mobility indicators (SUMI). Harmonisation Guideline. Final (web) version* (MOVE/B4/2017-358). Rupprecht Consult, TRT, Transport & Mobility Leuven, Polis, UITP, EuroCities. https://ec.europa.eu/transport/themes/urban/urban_mobility/sumi_en

Fan, W. (David), Machemehl, R. B., & Lownes, N. E. (2008). Carsharing: Dynamic Decision-Making Problem for Vehicle Allocation. *Transportation Research Record*, *2063*(1), 97–104. https://doi.org/10.3141/2063-12

FEDRO. (2021). *Mobility Pricing*. Federal Roads Office (FEDRO). https://www.astra.admin.ch/astra/de/home/themen/mobility-pricing.html

Fernando, N., Loke, S. W., & Rahayu, W. (2013). Mobile cloud computing: A survey. *Future Generation Computer Systems*, *29*(1), 84–106. https://doi.org/10.1016/j.future.2012.05.023

Fitzgerald, J., Mussomeli, A., Daecher, A., & Chandramouli, M. (2018). *Using smart sensors to drive supply chain innovation*. Deloitte.

Frankenfield, J. (2021). Smart Contracts. In *Investopedia*. https://www.investopedia.com/terms/s/smart-contracts.asp

FSO. (2020). *Passenger transport performance*. https://www.bfs.admin.ch/bfs/en/home/statistics/mobility-transport/passenger-transport/performance.html

Gartner. (n.d.). *Advanced Analytics*. Retrieved May 11, 2021, from https://www.gartner.com/en/information-technology/glossary/advanced-analytics

Gawron, J. H., Keoleian, G. A., De Kleine, R. D., Wallington, T. J., & Kim, H. C. (2018). Life Cycle Assessment of Connected and Automated Vehicles: Sensing and Computing Subsystem and Vehicle Level Effects. *Environmental Science & Technology*, *52*(5), 3249–3256. https://doi.org/10.1021/acs.est.7b04576

Gerte, R., Konduri, K. C., & Eluru, N. (2018). Is There a Limit to Adoption of Dynamic Ridesharing Systems? Evidence from Analysis of Uber Demand Data from New York City. *Transportation Research Record*, *2672*(42), 127–136. https://doi.org/10.1177/0361198118788462

GeSI, & Accenture Strategy. (2015). *#SMARTer2030. ICT Solutions for 21st Century Challenges*. https://smarter2030.gesi.org/

Google. (n.d.). *Accessibility in Google Maps*. Retrieved June 10, 2021, from https://support.google.com/maps/answer/6396990?co=GENIE.Platform%3DAndroid&hl=en-GB

Gösele, M., & Sandner, P. (2018). *Analysis of Blockchain Technology in the Mobility Sector* [FSBC Working Paper]. Frankfurt School Blockchain Center. https://philippsandner.medium.com/analysis-of-blockchain-technology-in-the-mobility-sector-1078e429615f

Grigorik, I. (2013). *High Performance Browser Networking*. O'Reilly Media, Inc. oreilly.com/catalog/errata.csp?isbn=9781449344764

Guerrero-Ibáñez, J., Zeadally, S., & Contreras-Castillo, J. (2018). Sensor Technologies for Intelligent Transportation Systems. *Sensors*, *18*(4), 1212. https://doi.org/10.3390/s18041212

Guizzo, E. (2018). *What Is a Robot? Top roboticists explain their definition of robot*. Robots. https://robots.ieee.org/learn/what-is-a-robot/

Gupta, A. K., & Arora, S. K. (2009). *Industrial Automation and Robotics*. Laxmi Publications.

Halder, S., Ghosal, A., & Conti, M. (2019). Secure OTA Software Updates in Connected Vehicles: A survey. *ArXiv:1904.00685 [Cs]*. http://arxiv.org/abs/1904.00685

Hallberg, D. (2009). *System for Predictive Life cycle Management of Buildings and Infrastructures*. http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-10312

Hämäläinen, M. (2020). Smart city development with digital twin technology. *Proceedings of the 33rd Bled EConference-Enabling Technology for a Sustainable Society*. 33rd Bled eConference-Enabling Technology for a Sustainable Society, Bled, Slovenia. https://doi.org/10.18690/978-961-286-362-3.20

Han, X., Grubenmann, T., Cheng, R., Wong, S. C., Li, X., & Sun, W. (2020). Traffic Incident Detection: A Trajectory-based Approach. *2020 IEEE 36th International Conference on Data Engineering (ICDE)*, 1866–1869. https://doi.org/10.1109/ICDE48307.2020.00190

Hårrskog, C., Magnusson, U., Hammarlund, S., Tufvesson, E., Henriksson, J., Nylander, A., & Lundgren, R. (2018). *Trafikverkets Omvärldsanalys 2018* (No. 978-91-7725-351–8). Trafikverket.

haveltec GmbH. (n.d.). *I lock it*. I Lock It. Retrieved June 10, 2021, from https://ilockit.bike/fahrrad-app-gegen-diebstahl/

Helm, J. M., Swiergosz, A. M., Haeberle, H. S., Karnuta, J. M., Schaffer, J. L., Krebs, V. E., Spitzer, A. I., & Ramkumar, P. N. (2020). Machine Learning and Artificial Intelligence: Definitions, Applications, and Future Directions. *Current Reviews in Musculoskeletal Medicine*, *13*(1), 69–76. https://doi.org/10.1007/s12178-020-09600-8

Hernandez Medel, C., Martinez Olague, M. A., Martin Olalla, A., & Garcia Sanz, M. A. (2008). Advanced fleet management systems for public transport. *Archives of Transport System Telematics*, *Vol. 1, iss. 1*, 42–46.

Hilty, L., & Bieser, J. C. T. (2017). *Opportunities and Risks of Digitalization for Climate Protection in Switzerland*. University of Zurich. http://www.zora.uzh.ch/id/eprint/141128/1/Study_Digitalization_Climate_Protection_Oct2017.pdf

Hilty, L., Wäger, P., Lehmann, M., Hischier, R., Ruddy, T., & Binswanger, M. (2004). *The future impact ICT on environmental sustainability. Fourth Interim Report. Refinement and Quantification.* (Technical Report Fourth Interim Report). Institute for Prospective Technological Studies (IPTS).

Hirz, M., Rossbacher, P., & Gulanová, J. (2017). Future trends in CAD – from the perspective of automotive industry. *Computer-Aided Design and Applications*, *14*(6), 734–741. https://doi.org/10.1080/16864360.2017.1287675

Hobbs, F. D., & Jovanis, P. P. (2018). Traffic control. In *Britannica*. https://www.britannica.com/technology/traffic-control

Hoffmann, T., & Prause, G. (2018). On the Regulatory Framework for Last-Mile Delivery Robots. *Machines*, *6*(3), 33. https://doi.org/10.3390/machines6030033

Hörcher, D., & Graham, D. J. (2020). MaaS economics: Should we fight car ownership with subscriptions to alternative modes? *Economics of Transportation*, *22*, 100167. https://doi.org/10.1016/j.ecotra.2020.100167

Hörl, S., Becker, F., Dubernet, T., & Axhausen, K. W. (2019). *Induzierter Verkehr durch autonome Fahrzeuge: Eine Abschätzung*. Schweizerische Vereinigung der Verkehrsingenieure und Verkehrsexperten (SVI), Bundesamt für Strassen.

Hossain, Md. F. (2019). Chapter Seven—Best Management Practices. In Md. F. Hossain (Ed.), *Sustainable Design and Build* (pp. 419–431). Butterworth-Heinemann. https://doi.org/10.1016/B978-0-12-816722-9.00007-0

IGI Global. (n.d.). *What is Digital Technology*. Retrieved May 11, 2021, from https://www.igi-global.com/dictionary/digital-technology/7723

Intelligent Transport. (2018). *Intelligent transportation systems market expected to reach $57.44 billion in 2024*. https://www.intelligenttransport.com/transport-news/64582/intelligent-transportation-system-market/

Itten, R., Hischier, R., Andrae, A. S. G., Bieser, J. C. T., Cabernard, L., Falke, A., Ferreboeuf, H., Hilty, L. M., Keller, R. L., Lees-Perasso, E., Preist, C., & Stucki, M. (2020). Digital transformation—Life cycle assessment of digital services, multifunctional devices and cloud computing. *The International Journal of Life Cycle Assessment*, *25*(10), 2093–2098. https://doi.org/10.1007/s11367-020-01801-0

ITU. (2017). *Minimum requirements related to technical performance for IMT-2020 radio interface(s)* (M Series Mobile, Radiodetermination, Amateur and Related Satellite Services). Report ITU-R M.2410-0.

Janai, J., Güney, F., Behl, A., & Geiger, A. (2020). Computer Vision for Autonomous Vehicles: Problems, Datasets and State of the Art. *Foundations and Trends® in Computer Graphics and Vision*, *12*(1–3), 1–308. https://doi.org/10.1561/0600000079

Jattke, M., Bieser, J. C. T., Blumer, Y., Itten, R., & Stucki, M. (2020). Environmental implications of service life extension of mobile devices. In Electronics Goes Green 2020+, Online, 1. September 2020 (pp. 163-170). Fraunhofer IZM.

Jonna AB. (n.d.). *Jonna*. Retrieved June 10, 2021, from https://jonnabike.se/

Kala, R. (2016). 4—Advanced Driver Assistance Systems. In R. Kala (Ed.), *On-Road Intelligent Vehicles* (pp. 59–82). Butterworth-Heinemann. https://doi.org/10.1016/B978-0-12-803729-4.00004-0

Kasliwal, A., Furbush, N. J., Gawron, J. H., McBride, J. R., Wallington, T. J., De Kleine, R. D., Kim, H. C., & Keoleian, G. A. (2019). Role of flying cars in sustainable mobility. *Nature Communications*, *10*(1), 1555. https://doi.org/10.1038/s41467-019-09426-0

Kellermann, R., Biehle, T., & Fischer, L. (2020). Drones for parcel and passenger transportation: A literature review. *Transportation Research Interdisciplinary Perspectives*, *4*, 100088. https://doi.org/10.1016/j.trip.2019.100088

Kem, O., Balbo, F., & Zimmermann, A. (2017). Traveler-Oriented Advanced Traveler Information System based on Dynamic Discovery of Resources: Potentials and Challenges. *Transportation Research Procedia*, *22*, 635–644. https://doi.org/10.1016/j.trpro.2017.03.059

Khan, M., Alvi, B., Safi, E., & Khan, I. (2018). *Drones for Good in Smart Cities:A Review*. International Conference on Electrical, Electronics, Computers, Communication, Mechanical and Computing (EECCMC), India.

Killeen, P., Ding, B., Kiringa, I., & Yeap, T. (2019). IoT-based predictive maintenance for fleet management. *Procedia Computer Science*, *151*, 607–613. https://doi.org/10.1016/j.procs.2019.04.184

KonSULT. (2016a). Integrated ticketing. In *Policy Instruments: A Policy Guidebook*. University of Leeds. http://www.konsult.leeds.ac.uk/pg/70/

KonSULT. (2016b). Road user charging. In *Policy Instruments: A Policy Guidebook*. University of Leeds. http://www.konsult.leeds.ac.uk/pg/01/

Kornhauser, A. L. (1987). Exploring transportation problems using interactive computer graphics. *Computers & Graphics*, *11*(3), 231–239. https://doi.org/10.1016/0097-8493(87)90002-1

Krail, M., Hellekes, J., Schneider, U., Dütschke, E., Schellert, M., Rüdiger, D., Steindl, A., Luchmann, I., Waßmuth, V., Flämig, H., Schade, W., & Mader, S. (2019). *Energie- und Treibhausgaswirkungen des automatisierten und vernetzten Fahrens im Straßenverkehr*. Fraunhofer ISI, Fraunhofer IML, PTV AG, PTV Transport Consult GmbH, TU Hamburg-Haburg - VPL, M-Five.

Kramers, A. (2014). Designing next generation multimodal traveler information systems to support sustainability-oriented decisions. *Environmental Modelling & Software*, *56*, 83–93. https://doi.org/10.1016/j.envsoft.2014.01.017

Kramers, A., Ringenson, T., Sopjani, L., & Arnfalk, P. (2018). AaaS and MaaS for reduced environmental and climate impact of transport. *EPiC Series in Computing*, *52*, 137–152. https://doi.org/10.29007/cx17

Lakshmi Narayanan, R. G., & Ibe, O. C. (2015). 6—Joint Network for Disaster Relief and Search and Rescue Network Operations. In D. Câmara & N. Nikaein (Eds.), *Wireless Public Safety Networks 1* (pp. 163–193). Elsevier. https://doi.org/10.1016/B978-1-78548-022-5.50006-6

Lubello, V., & Bousse, Y. (2019). *Review of new mobility services and technologies and set-up of knowledge*. Gecko.

Mitschele, A. (n.d.). Blockchain. In *Gabler Wirtschaftslexikon*. Retrieved May 11, 2021, from https://wirtschaftslexikon.gabler.de/definition/blockchain-54161

Mokhtarian, P. (1990). A typology of relationships between telecommunications and transportation. *Transportation Research Part A: General*, *24*(3), 231–242. https://doi.org/10.1016/0191-2607(90)90060-J

Mokhtarian, P. (2002). Telecommunications and Travel: The Case for Complementarity. *Journal of Industrial Ecology*, *6*(2), 43–57. https://doi.org/10.1162/108819802763471771

Mokhtarian, P., Salomon, I., & Handy, S. (2006). The Impacts of Ict on leisure Activities and Travel: A Conceptual Exploration. *Transportation*, *33*(3), 263–289. https://doi.org/10.1007/s11116-005-2305-6

Moreau, H., de Jamblinne de Meux, L., Zeller, V., D'Ans, P., Ruwet, C., & Achten, W. M. J. (2020). Dockless E-Scooter: A Green Solution for Mobility? Comparative Case Study between Dockless E-Scooters, Displaced Transport, and Personal E-Scooters. *Sustainability*, *12*(5), 1803. https://doi.org/10.3390/su12051803

Müller, M., Behnke, D., Bok, P.-B., Peuster, M., Schneider, S., & Karl, H. (2019). 5G as Key Technology for Networked Factories: Application of Vertical-specific Network Services for Enabling Flexible Smart Manufacturing. *2019 IEEE 17th International Conference on Industrial Informatics (INDIN)*, *1*, 1495–1500. https://doi.org/10.1109/INDIN41052.2019.8972305

Münzel, K., Boon, W., Frenken, K., & Vaskelainen, T. (2018). Carsharing business models in Germany: Characteristics, success and future prospects. *Information Systems and E-Business Management*, *16*(2), 271–291. https://doi.org/10.1007/s10257-017-0355-x

Nguyen, T. H., Partala, J., & Pirttikangas, S. (2019). Blockchain-Based Mobility-as-a-Service. *2019 28th International Conference on Computer Communication and Networks (ICCCN)*, 1–6. https://doi.org/10.1109/ICCCN.2019.8847027

O'Brien, W., & Yazdani Aliabadi, F. (2020). Does telecommuting save energy? A critical review of quantitative studies and their research methods. *Energy and Buildings*, *225*, 110298. https://doi.org/10.1016/j.enbuild.2020.110298

OECD. (2015). *The Development of Fixed Broadband Networks* (OECD Digital Economy Paper No. 239). OECD. 10.1787/5jz2m5mlb1q2-en

OECD. (2021). *Passenger transport (indicator)*. 10.1787/463da4d1-en

Pawlak, J., Le Vine, S., Polak, J., & Kopp, J. (2015). *ICT and physical mobility: State of knowledge and future outlook*. Institute for Mobility research (ifmo), Imperial College London.

Pernestål Brenden, A., Kristoffersson, I., & Mattsson, L.-G. (2017). *Future scenarios for self-driving vehicles in Sweden*. http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-209159

Petterson, F. (2019). *An international review of experiences from on-demand public transport services* (K2 working paper 2019:5). Lund University. https://www.researchgate.net/publication/333619258_An_international_review_of_experiences_from_on-demand_public_transport_services

Pouri, M. J., & Hilty, L. M. (2021). The digital sharing economy: A confluence of technical and social sharing. *Environmental Innovation and Societal Transitions*, *38*, 127–139. https://doi.org/10.1016/j.eist.2020.12.003

Rayes, A., & Salam, S. (2017). The Things in IoT: Sensors and Actuators. In A. Rayes & S. Salam (Eds.), *Internet of Things From Hype to Reality: The Road to Digitization* (pp. 57–77). Springer International Publishing. https://doi.org/10.1007/978-3-319-44860-2_3

Remane, G., Hanelt, A., Nickerson, R., Tesch, J., & Kolbe, L. (2016). *A Taxonomy of Carsharing Business Models*. Thirty Seventh International Conference on Information Systems, Dublin.

Repschläger, J., Pannicke, D., & Zarnekow, R. (2010). Cloud Computing: Definitionen, Geschäftsmodelle und Entwicklungspotenziale. *HMD Praxis der Wirtschaftsinformatik*, *47*(5), 6–15. https://doi.org/10.1007/BF03340507

Ringenson, T., Arnfalk, P., Kramers, A., & Sopjani, L. (2018). Indicators for Promising Accessibility and Mobility Services. *Sustainability*, *10*(8), 2836. https://doi.org/10.3390/su10082836

Rodrigue, J.-P. (2020). The Digitalization of Mobility. In *The Geography of Transport Systems* (Vol. 5). Routledge. https://transportgeography.org/contents/chapter2/information-technologies-and-mobility/digitalization-mobility/

Ryan, L. (2020). Ride-hailing vs. Ridesharing vs. Carpooling: What's the difference? *Scoop*. https://www.takescoop.com/resources/ridesharing-or-carpooling-whats-the-difference

SAE International. (2016). *Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles* (J3016 JAN2014).

Samuylova, E. (2019). *What is the Difference Between AI, Machine Learning and Data Science?* Mechanica.Ai. http://mechanica.ai/blog/what-is-the-difference-between-ai-machine-learning-and-data-science

Sehrawat, D., & Gill, N. S. (2019). Smart Sensors: Analysis of Different Types of IoT Sensors. *2019 3rd International Conference on Trends in Electronics and Informatics (ICOEI)*, 523–528. https://doi.org/10.1109/ICOEI.2019.8862778

Selcuk, S. (2017). Predictive maintenance, its implementation and latest trends. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *231*(9), 1670–1679. https://doi.org/10.1177/0954405415601640

Shaheen, S., Cohen, A., Chan, N., & Bansal, A. (2020). Chapter 13 - Sharing strategies: Carsharing, shared micromobility (bikesharing and scooter sharing), transportation network companies, microtransit, and other innovative mobility modes. In E. Deakin (Ed.), *Transportation, Land Use, and Environmental Planning* (pp. 237–262). Elsevier. https://doi.org/10.1016/B978-0-12-815167-9.00013-X

Sims, R., Schaeffer, F., Creutzig, X., Cruz-Núñez, M. D., Dimitriu, D., Figueroa Meza, M. J., Fulton, L., Kobayashi, S., Lah, O., McKinnon, A., Newman, P., Ouyang, M., Schauer, J. J., Sperling, D., & Tiwari, G. (2014). Transport. In *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovern- mental Panel on Climate Change*. Cambridge University Press.

Sjöman, M., Ringenson, T., & Kramers, A. (2020). Exploring everyday mobility in a living lab based on economic interventions. *European Transport Research Review*, *12*(1), 5. https://doi.org/10.1186/s12544-019-0392-2

Smart Sense. (2020). The Evolution of Sensor Technology. *Smart Sense*. https://blog.smartsense.co/evolution-sensor-technology

Sochor, J., Arby, H., Karlsson, I. C. M., & Sarasini, S. (2018). A topological approach to Mobility as a Service: A proposed tool for understanding requirements and effects, and for aiding the integration of societal goals. *Research in Transportation Business & Management*, *27*, 3–14. https://doi.org/10.1016/j.rtbm.2018.12.003

Stapleton, L., Sorrell, S., & Schwanen, T. (2016). Estimating direct rebound effects for personal automotive travel in Great Britain. *Energy Economics*, *54*, 313–325. https://doi.org/10.1016/j.eneco.2015.12.012

Statista Research Department. (2021a). *Mobile app verticals with the highest install and user base growth in 2018*. Statista. https://www.statista.com/statistics/251096/fastest-growing-shopping-app-categories/

Statista Research Department. (2021b). *Number of available apps in the Apple App Store from 2008 to 2020*. Statista. https://www.statista.com/statistics/268251/number-of-apps-in-the-itunes-app-store-since-2008/

Statista Research Department. (2021c). *Number of mobile app downloads worldwide from 2016 to 2020*. Statista. https://www.statista.com/statistics/271644/worldwide-free-and-paid-mobile-app-store-downloads/

Stevens, M. N., & Atkins, E. M. (2018). Geofencing in Immediate Reaches Airspace for Unmanned Aircraft System Traffic Management. In *2018 AIAA Information Systems-AIAA Infotech @ Aerospace*. American Institute of Aeronautics and Astronautics. https://doi.org/10.2514/6.2018-2140

Sussman, J. S. (2005). *Perspectives on Intelligent Transportation Systems (ITS)*. Springer US. https://doi.org/10.1007/b101063

Taiebat, M., Stolper, S., & Xu, M. (2019). Forecasting the Impact of Connected and Automated Vehicles on Energy Use: A Microeconomic Study of Induced Travel and Energy Rebound. *Applied Energy*, *247*, 297–308. https://doi.org/10.1016/j.apenergy.2019.03.174

Talukder, M. Z., Towqir, S. S., Remon, A. R., & Zaman, H. U. (2017). An IoT based automated traffic control system with real-time update capability. *2017 8th International Conference on Computing, Communication and Networking Technologies (ICCCNT)*, 1–6. https://doi.org/10.1109/ICCCNT.2017.8204095

Teralytics. (2021). *Teralytics*. https://www.teralytics.net/de/

Thomas, K. D., Quinn, E. L., Mauck, J. L., & Bockhorst, R. M. (2015). *Digital Sensor Technology* (INL/CON-14-33917). Idaho National Lab. (INL), Idaho Falls, ID (United States). https://www.osti.gov/biblio/1179383-digital-sensor-technology

Tian, B., Yao, Q., Gu, Y., Wang, K., & Li, Y. (2011). *Video processing techniques for traffic flow monitoring: A survey*. https://ieeexplore.ieee.org/document/6083125

Tirachini, A. (2020). Ride-hailing, travel behaviour and sustainable mobility: An international review. *Transportation*, *47*(4), 2011–2047. https://doi.org/10.1007/s11116-019-10070-2

Tirachini, A., & Antoniou, C. (2020). The economics of automated public transport: Effects on operator cost, travel time, fare and subsidy. *Economics of Transportation*, *21*, 100151. https://doi.org/10.1016/j.ecotra.2019.100151

Paris Agreement, FCCC/CP/2015/10/Add.1 § Art. 2 & Art. 4 (2015). http://unfccc.int/files/meetings/paris_nov_2015/application/pdf/paris_agreement_english_.pdf

United Nations. (2016). *Mobilizing sustainable transport for development*. https://sustainabledevelopment.un.org/index.php?page=view&type=400&nr=2375&menu=1515

Vaddadi, B., Pohl, J., Bieser, J. C. T., & Kramers, A. (2020). Towards a conceptual framework of direct and indirect environmental effects of co-working. *Proceedings of the 7th International Conference on ICT for Sustainability*, 27–35. https://doi.org/10.1145/3401335.3401619

VanDerHorn, E., & Mahadevan, S. (2021). Digital Twin: Generalization, characterization and implementation. *Decision Support Systems*, *145*, 113524. https://doi.org/10.1016/j.dss.2021.113524

Vosooghi, R., Kamel, J., Puchinger, J., Leblond, V., & Jankovic, M. (2019). Robo-Taxi service fleet sizing: Assessing the impact of user trust and willingness-to-use. *Transportation*, *46*(6), 1997–2015. https://doi.org/10.1007/s11116-019-10013-x

Warland, L., & Hilty, L. (2016). *Factsheet: Business Travel*. University of Zurich. https://www.sustainability.uzh.ch/dam/jcr:b885ad2f-bf2b-4a6a-bcde-e3de15598459/2016-08-17_Factsheet_business%20travel.pdf

Weinmann, M., Schneider, C., & Brocke, J. vom. (2016). Digital Nudging. *Business & Information Systems Engineering*, *58*(6), 433–436. https://doi.org/10.1007/s12599-016-0453-1

You, S., Krage, M., & Jalics, L. (2005). *Overview of Remote Diagnosis and Maintenance for Automotive Systems* (SAE Technical Paper No. 2005-01–1428). SAE International. https://doi.org/10.4271/2005-01-1428

Zahedmanesh, A., Muttaqi, K., & Sutanto, D. (2019). Direct Control of Plug-In Electric Vehicle Charging Load Using an In-House Developed Intermediate Control Unit. *IEEE Transactions on Industry Applications*, *55*(3), 2208–2218. https://doi.org/10.1109/TIA.2018.2890786

Zheng, H., Chang, W., & Wue, J. (2019). Traffic flow monitoring systems in smart cities: Coverage and distinguishability among vehicles. *Journal of Parallel and Distributed Computing*, *127*, 224–237. https://doi.org/10.1016/j.jpdc.2018.07.008

Zhu, A., & Zhang, C. (2020). The Value and Application of Car Head-Up Display in Interactive Design. *Proceedings of the 2nd International Conference on Artificial Intelligence and Advanced Manufacture*, 478–483. https://doi.org/10.1145/3421766.3421796

Zijlstra, T., & Vanoutrive, T. (2018). The employee mobility budget: Aligning sustainable transportation with human resource management? *Transportation Research Part D: Transport and Environment*, *61*, 383–396. https://doi.org/10.1016/j.trd.2017.10.005