Smart Mobility

Exploring Foundational Technologies and Wider Impacts

Alaa Khamis

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Alaa Khamis
Courtice, ON, Canada

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To my beautiful wife Nermein and my lovely children Renad and Kareem. You are the joy of my life.

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Preface

Nowadays, we are witnessing several paradigm shifts in mobility systems and services. Cities are decarbonizing the transportation sector and are moving from car-centric mobility to multimodal mobility, from restricted mobility in two-dimensional streets to 3D mobility, from rigid-schedule mobility to mobility on demand and on an as-needed basis, and from fragmented unconnected mobility to seamless integrated mobility. Mobility companies move from the manufacturing and trade economy to the service economy or servitization such as Mobility-as-a-Service (MaaS) as the neo-liberalization of people and freight transportation and from the unsustainable "number of cars sold"-based revenue model to "vehicle miles traveled (VMT)-based," infonomics-based data and customer experience monetization and passenger economy-based revenue models. Delivery service providers move from conventional slow, rigid, and nontransparent last-mile delivery to fast, elastic, and transparent last-mile delivery services. People move from ownership to usership and from passive mobility to active and zero-impact mobility. Different foundational technologies, technology enablers, and mobility disruptors are behind these paradigm shifts.

This book gives a holistic view of smart mobility systems and services and describes their foundational technologies, technology enablers, and disruptors. The market size of these technologies, their potential growth, and their eco-socioeconomic implications are highlighted in this book. Impacts of the COVID-19 pandemic on consumer behaviors and preferences and the expected short-term disruptions and longer-term structural changes in different aspects of mobility systems especially in micromobility, shared mobility, public transit, and contactless last-mile delivery services are also discussed.

The development of topics in this book follows a logical flow progressing from foundational technologies to technology enablers to smart mobility disruptors. The following is a concise chapter-by-chapter description of the contents of the book:

- Chapter 1 provides an overview of people-centric smart cities.
- Chapter 2 presents the smart mobility triad that comprises three complementary factors, namely, technology, governance, and city planning. These three components are not separate components as they impact each other.

- Chapter 3 introduces Position, Navigation, and Timing (PNT), Geographic Information System (GIS), wireless communication, mobile cloud computing (MCC), blockchain, Internet of Things (IoT), Artificial Intelligence (AI), robotics, and electrification as foundational technologies for smart mobility systems and services.
- Chapter 4 discusses several technology enablers for smart mobility such as intelligent infrastructure, connected mobility, automated mobility, e-mobility, micromobility, active/soft mobility, inclusive mobility, and Context Awareness Systems (CAS).
- Chapter 5 sheds light on potential smart mobility disruptors such as disruptive mobility platforms (autonomous ground vehicles, urban air mobility (UAM), river taxis, automated people movers (APMs), hyperloop, and urbanloop), shared mobility, Mobility-as-a-Service (MaaS), mobility on demand (MOD), seamless integrated mobility systems (SIMS), last-mile delivery, Vehicle-as-a-Service (VaaS), gig economy, and passenger economy.
- Finally, impacts of the COVID-19 pandemic on smart mobility systems and services are discussed in Chapter 6.

I do believe that the future mobility is people-centric, software-defined, connected, and electric. In spite of recent rapid development, smart mobility is still in its infancy. There is a growing need to use different mentioned foundational technologies, technology enablers, and disruptors to enhance the relationship between customers and mobility providers and to achieve affordable, inclusive, and seamless integration between different mobility services. The legal and regulatory environment around several smart mobility technologies needs to be well developed taking into consideration opinions and concerns of different stakeholders. Moreover, evolutionary and revolutionary changes in the city planning should be considered to accommodate the emerging services of smart mobility.

This book is intended for working professionals, training centers, and academic institutions. The book serves a wide range of audience including university students, researchers, mobility engineers, technologists, and city planners looking for a holistic vision and new ideas about future mobility technologies and services. The book gives the reader a comprehensive and easy-to-digest introduction to the current and emerging smart mobility systems focusing on foundational technologies, technology enablers, and disruptors that will shape the future of mobility.

While the book describes many future possibilities, some surprising achievements are already made and publicly used. We all enjoy and rely every day on shared mobility services, connected mobility, e-mobility, active mobility, micromobility, and same-day and instant last-mile delivery services. Moreover, in the not too distant future, we will enjoy safe and entertaining self-driving vehicles (SDVs) as a third living space with consumer-centric products and services; we will be able to use self-driving vehicles as a mobile motel, beauty salon, mobile store, and mobile clinic; we will have our online orders shipped to our doorstep by delivery droids; we will travel safely and conveniently in zero-emission hyperloops, autonomous air taxis, air metro, or autonomous boats; seamless integration between different mobility modes will be the norm; and finally affordable inclusive and sustainable mobility will be achieved. I hope you will enjoy this exciting journey into the future of people and goods mobility.

CHAPTER

1

Toward a People-Centric Smart City

Population shift from rural to urban areas driven by social and economic needs led to massive mobility challenges and several negative impacts in contemporary cities related to road safety, congestion, and emissions. Smart cities consider people and the environment as the central focus for a better quality of life, reasonable consumption of natural resources, and sustainable development and prosperity. In this chapter, implications of conventional car-centric cities and the need for people-centric smart cities are highlighted. Smart mobility is presented in this chapter as one of the main pillars of smart cities of the future.

1.1. World Urbanization Problems

According to the latest World Urbanization Prospects report published by the United Nations in 2018, the number of people living in cities will increase from 3.6 billion to 6.3 billion by 2050 (UN DESA, 2018). The global population will be two-thirds urban, and the world will be only one-third rural, roughly

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the reverse of the global rural-urban population distribution of the mid-twentieth century. According to a report from Navigant Research, currently there are about 1.2 billion vehicles on the road. The total number of cars worldwide could reach 2 billion by 2035, not including motorcycles. The negative implications of this conventional car-centric world include safety, congestion, and environmental impacts.

Road traffic accidents are enormously costly in terms of human suffering, economic loss, and wildlife and environmental impact. According to World Health Organization (WHO), the number of deaths on the world's roads remains unacceptably high with 1.35 million people dying each year or 3,698 deaths a day, making road traffic accidents the eighth leading cause of death for people of all ages and the first cause of death for children and young adults (World Health Organization, 2018). The number of traffic fatalities is expected to rise to 2.2 million by 2030. These traffic fatalities are the leading cause of death for 5–14-year-olds in high-income countries, representing 19% of all fatalities (Rothman et al., 2020).

Global economy loses $1 trillion worth of productivity annually sitting in traffic (McKinsey Global Institute, 2013). The study conducted by the traffic data company INRIX has ranked Bogota as the most congested city in the world with an average of 191 hours driving time spent in congestion. The same study ranked Toronto as the most congested city in Canada and the 19th most traffic-congested city across the globe in 2019 with an average of 135 hours driving time spent in congestion. According to INRIX, Canadians are spending an average of 27 hours a year stuck in traffic. American commuters spend about a week of their lives in traffic each year. Traffic Index provides real-time ranking and analytics about 416 cities around the world.

Conventional transport fuels are large emitters of pollutants, making transport a large contributor of global greenhouse gas (GHG) emissions. For example, according to the US Environmental Protection Agency (EPA), GHG emissions from transportation account for about 28% of the total US greenhouse gas emissions, making it the largest contributor of US GHG emissions. The current and expected growth in conventional transport fuel demand, particularly for diesel, will cause a tremendous public health burden and will accelerate global climate change (Hoornweg and Freire, 2013). Conventional vehicles with an internal combustion engine (ICE or ICEV) are one of the main causes of greenhouse gas. Figure 1-1 illustrates the carbon footprint and space required per mobility mode. Beside the high carbon footprint, conventional mobility modes take up way too much space in cities for paved roads and parking. Many downtowns devote 50–60% of their scarce real estate to vehicles (Plumer, 2016).

1.2. People-Centric Smart Cities

The aforementioned challenges cannot be solved by simply building more roads for the vehicles. Braess' paradox (Braess et al., 2005) shows the fact that adding one or more roads to a road network does not improve the traffic and sometimes worsens the traffic flow. Braess' paradox is not exactly a paradox and represents a counterintuitive result in which, like the prisoner's dilemma, collective good gets sacrificed because of self-interest. An interesting study conducted by the Transformative Urban Mobility Initiative (TUMI) concluded that a restructured multimodal mobility corridor can accommodate in total 74,000 people (2,000 in cars, 16,000 pedestrians, 44,000 in light rail, and 14,000 cyclists) compared to a traditional car-centric corridor that can carry only 24,000 people (8,000 in cars and 16,000 pedestrians).

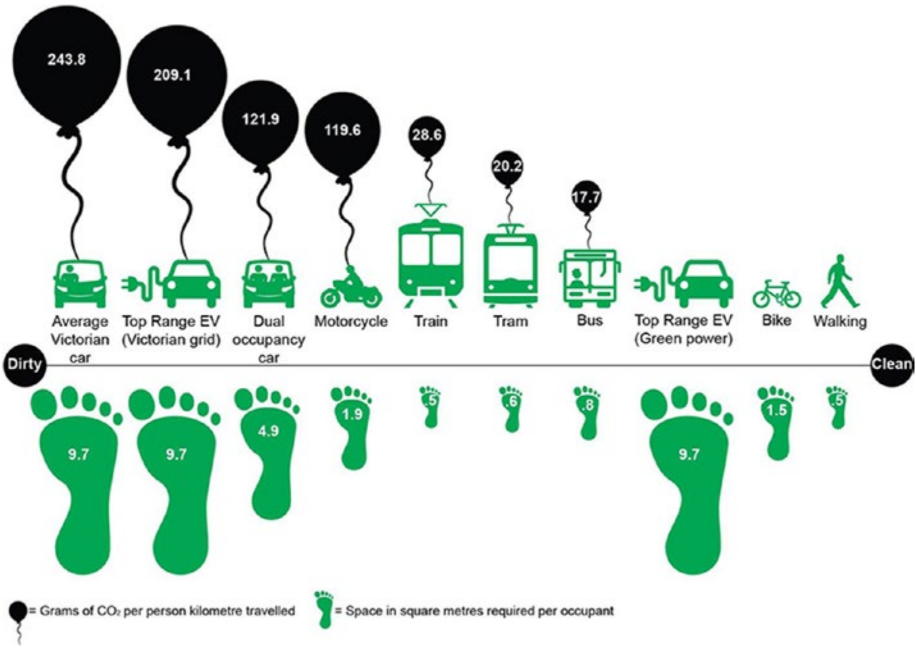

Figure 1-1. Carbon Footprint and Space Required per Occupant. Source: Courtesy of the Institute for Sensible Transport

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■ **Note** A highway 20 lanes wide would be required to carry in automobiles the number of people now being served by Toronto's subway.

This arises the need to develop and deploy sustainable mobility systems able to change the current conventional car-centric cities to people-centric smart cities. Sustainability is meeting the needs of the present without compromising the ability of future generations to meet their own needs (Brundtland et al., 1987). In recent years, the concept of "smart city" has received an increasing amount of attention from researchers, developers, and policy makers in academia, government laboratories, and industry.

Important According to market forecasters and analysts like Grand View Research, the global smart cities' market size is expected to reach $463.9 billion by 2027, registering a CAGR of 24.7% from 2020 to 2027.

There have been many definitions of a smart city given over the years. Smartness in the context of smart cities includes monitoring, control, and optimization to bring in efficiency and bottom-line benefits as well as environmental improvements. A city can be defined as "smart" when social capital and modern information and communication infrastructure fuel sustainable economic development and a high quality of life (Caragliu et al., 2011). In other words, a smart city uses digital technologies or information and communication technologies to enhance quality and performance of urban services, to reduce costs and resource consumption, and to engage more effectively and actively with its citizens. MIT defines a smart city as "systems of systems with digital nervous systems, intelligent responsiveness, and optimization at every level of system integration."

According to a report by the World Bank, smart cities adopt technical and information platforms to better manage the use of their resources, improve management, monitor developments, develop new business models, and help citizens to make informed decisions about the use of resources (Hoornweg and Freire, 2013).

Cities are very heterogeneous entities that integrate a wide variety of components with more similarities than differences. Digitization, automation, connectivity, and data analytics are key aspects to achieve seamless integration between these components. According to a survey conducted by PwC involving about 64 cities (Galal et al., 2011), after finance, the second most important barrier to smart city strategy implementation is prioritization. Cities must first address their very basic needs: security, health, and basic infrastructure such as clean water and sanitation. These infrastructures should be also optimized for the best use by the citizens. If these basic needs are already met, the focus shifts to safety and security needs, roads and transport infrastructure, and educational access, as the city moves from basic industrial production to becoming an informational society. In more developed cities, the focus will be on environmental needs, social integration, culture and leisure, as well as information and communication technologies as an enabler for a knowledge-based society. At the next level are the smart cities, which are defined as a world leader able to maximize its performance across all capitals. Beyond that comes the level of self-actualization, when cities explore new paradigms and set new standards for the quality of life and are willing to share their experiences to help other cities advance (Galal et al., 2011).

Smart mobility, smart living, smart society, smart environment, smart economy, and smart governance are the main pillars of a smart city as illustrated in Figure 1-2. Digitalization, automation, connectivity, and analytics are four main enablers for monitoring, control, and optimization in each of these six pillars. Smart mobility addresses the availability of information and communication infrastructure and safety and the sustainability of mobility systems. Local and international accessibility of transport systems are also important aspects of smart mobility. More details about smart mobility are provided in the next section.

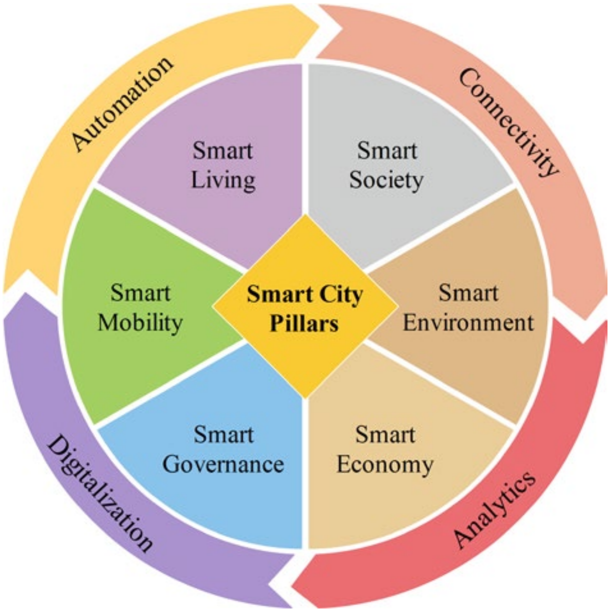

Figure 1-2. Smart City Pillars

Smart living comprises various aspects of quality of life such as culture, health, safety, housing, tourism, and so on. Agile civil society, level of qualification or education of the citizens, social inclusion, the quality of social interactions regarding integration and active participation in public life, and the openness toward the "outer" world are indicators for smart societies. Smart environment is described by attractive natural conditions (e.g., climate and green space), pollution, resource management, and also efforts toward environmental protection. Smart economy includes factors all around economic competitiveness as innovation, entrepreneurship, trademarks, productivity and flexibility of the labor market, as well as the integration in the (inter) national market (Giffinger et al., 2007). Finally, smart governance comprises aspects of political participation, services for citizens, as well as the functioning of the administration.

There are several smart city projects and initiatives across the world. According to the latest Smart City Index report published in 2020 (IMD and SUTD, 2020), the top ten smart cities in the world are Singapore, Helsinki, Zurich, Auckland, Oslo, Copenhagen, Geneva, Taipei City, Amsterdam, and New York as shown in Table 1-1. This index ranks 109 cities based on economic and technological data, as well as by their citizens' perceptions of how "smart" their cities are.

Table 1-1. Top Ten Smart Cities in the World as per Smart City Index (IMD and SUTD, 2020)

City	Country	2020 Ranking	2019 Ranking	Change
Singapore	Singapore	1	1	0
Helsinki	Finland	2	8	+6
Zurich	Switzerland	3	2	-1
Auckland	New Zealand	4	6	+2
Oslo	Norway	5	3	-2
Copenhagen	Denmark	6	5	+1
Geneva	Switzerland	7	4	+3
Taipei	Taiwan	8	7	+1
Amsterdam	Netherlands	9	11	+2
New York	United States	10	38	+28

The Line was revealed in January 2021 as a fully sustainable smart city to be built as part of Neom, a planned cross-border city in the Tabuk province of northwestern Saudi Arabia. Neom was announced in 2017 and is part of Saudi Arabia's Vision 2030 drive to diversify its economy and become less reliant on oil. The Line is a linear 100-mile-long city with no cars or streets, with everything its inhabitants need accessible within a five-minute walk. The vision of this mega city is to be zero-energy walkable communities for a million people. The Line is inspired by Paolo Soleri's Lean Linear City concept (Soleri et al., 2012) where pedestrian-based communities are oriented around linear local and regional transportation systems.

1.3. Smart Mobility as a Key Enabler to Sustainable Development

In recent years, smart mobility systems and services have received an increasing amount of attention from major automakers, suppliers, academia, and governmental institutions due to their foreseen advantages in dealing with the negative implications of the conventional automotive technology in the current car-centric world such as safety problems, congestion problems, and environmental problems. General Motors (GM) is leading the way toward a future with zero crashes, zero emissions, and zero congestion (General Motors, 2018). The main objectives of this vision are summarized as follows:

- **Zero Crashes to Save Lives:** Advanced driver assistance systems (ADAS) and automated driving vehicles will reduce injuries and fatalities and improve access to mobility for those who currently cannot drive due to age, disability, or otherwise.
- **Zero Emissions to Leave Our Children a Healthier Planet:** Conventional internal combustion engine (ICE) vehicles release almost 2 billion tons of carbon dioxide into the atmosphere every year. Electric vehicles (EVs) will eliminate the emission contributing to a better environment. In early 2021, GM announced a plan to become carbon neutral in its global products and operations by 2040. As part of this plan, the company will offer 30 new electric vehicles globally by 2025.
- **Zero Congestion to Give the Customers Back Their Precious Time:** In the United States, commuters spend about a week of their lives in traffic each year. That's a week not spent with those we love, doing what we want to do, and being where we want to be. Shared mobility will create better use of time and space to reduce the congestion.

Aligned with 17 Sustainable Development Goals (SDGs) adopted by UN Member States, smart mobility can play an instrumental role in achieving many of these goals. The Sustainable Mobility for All (SuM4All[1]) initiative is a global partnership that aims to achieve sustainable mobility and help implement the SDGs. In order to transform the transport sector, SuM4All developed a Global Tracking Framework (GTF) for transport, complementing the targets and indicators in the SDGs. This global framework is featured in the Global

[1] www.sum4all.org/

Mobility Report (SuM4All, 2017), which provides the first-ever assessment of all modes of transport across the globe. GTF provides crucial information and tools to inform transport policy and investment decisions and provides a baseline for measuring progress toward sustainable mobility. According to the Global Mobility Report published by SuM4All, SDGs 3 and 11 are two main goals directly related to mobility. SDG 3 focuses on “Good Health and Well-Being” with target 3.6 about reducing global deaths and injuries from traffic accidents. This SDG target 3.6 identifies a quantitative target for road safety: by 2020, halve the number of global deaths and injuries from road traffic accidents. SDG 11 is about “Sustainable Cities and Communities” with target 11.2 that emphasizes on providing access to safe, affordable, accessible, and sustainable transport systems for all. The report illustrates how sustainable transport systems are necessary to provide food security (SDG 2: Zero Hunger), healthcare (SDG 3: Good Health and Well-Being), access to schools (SDG 4: Quality Education), and employment for women (SDG 5: Gender Equality).

Several indices are proposed to help city leaders in assessing and improving the quality of mobility systems. For example, the HERE Technologies Urban Mobility Index[2] is a comprehensive index that addresses how cities around the world are dealing with the challenges of mobility across four major themes, namely, sustainability, connectivity, affordability, and innovation. Sustainability reflects low-carbon mobility as a way to improve health and quality of life. Connectivity measures the availability of information and communication infrastructure such as intelligent transport systems to better manage the traffic and improve the public transport efficiency. Affordable mobility changes how a city moves, enabling the flow of people, boosting economic potential, and enhancing social well-being. Innovation reflects how cities respond to changing mobility demands with innovative solutions. The Deloitte City Mobility Index (DCMI)[3] is another index to gauge the health of the mobility system and the city readiness to embrace the future. Three major themes are assessed in this index, namely, performance and resilience (congestion, reliability, safety, integrated mobility, and modal diversity), vision and leadership (vision and strategy, investment, innovation, regulatory environment, environmental sustainability initiatives), and service and inclusion (public transport density, affordability, air quality, customer satisfaction, and accessibility). Similarly, the Urban Mobility Innovation Index (UMii)[4] provides insights into urban mobility and innovation in cities based on evaluating three main aspects: readiness (strategy, capability, and soundness), deployment (regulation, investment, and engagement), and

[2]https://urbanmobilityindex.here.com/
[3]https://bit.ly/3chv8YN
[4]http://umi-index.org/

livability (connectivity, well-being, and environment). Arthur D. Little's Urban Mobility Index 3.0 is another index that assesses the mobility maturity, innovativeness, and performance in different cities using 27 indicators (Van Audenhove et al., 2018).

1.4. Summary

Smart mobility is one of the main pillars that characterizes smart cities and maintains their sustainability as a way to deal with continuously growing world urbanization and its expected impacts on public health, congestion, and accelerated global climate change. Mobility is now being seen as an information service with physical transportation products, rather than a transportation product with additional services (Ho and Bright, 2018). This is manifested in different smart mobility services we are using nowadays such as shared mobility services, Mobility-as-a-Service (MaaS), mobility on demand, and last-mile delivery services to name just a few. However, the widespread deployment and the societal acceptance of smart mobility systems and their sustainability depend on the advances in not only the technology domain but also the availability of governing policies, regulations, and laws and the proper planning/replanning of the cities to match with the requirements of these emerging and continuously evolving mobility systems and services. More details about smart mobility are provided in the next chapters.

CHAPTER

2

Smart Mobility Triad

Mobility is the ability and potential of passengers to travel and freight to be transported. According to the Universal Declaration of Human Rights (UDHR) adopted by the United Nations General Assembly (Flowers, 1998), mobility is a core human right and a basic need and foundation of social, economic, and cultural exchanges of people, businesses, and societies. The Sustainable Mobility for All[1] initiative formally established in 2017 aims at achieving sustainable mobility through focusing on the following four goals:

- **Safety:** Drastically reduce fatalities, injuries, and crashes.
- **Green:** Minimize the environmental footprint of mobility (greenhouse gas emissions, noise, and air pollution).
- **Access:** Connect all people, including women and communities, to economic and social opportunities.
- **Efficiency:** Optimize the predictability, reliability, and cost effectiveness of mobility.

Smart mobility is the promotion of sustainable mobility that guarantees seamless access to different modes of mobility and enables people or cargo to

[1] https://sum4all.org/

A. Khamis, *Smart Mobility*, https://doi.org/10.1007/978-1-4842-7101-8_2

get from one place to another in a way that is safe, clean, and most efficient (fast, convenient, comfortable, productive, and cheap). Smart mobility is built on five principles, namely, safety, flexibility, efficiency, integration, and clean technology.

Important According to Reportlinker, the global market size of smart mobility is expected to reach $91 billion by 2026, rising at a market growth of 18.4% CAGR during the forecast period. The rewards of unlocking smart mobility could be vast, as this market is expected to generate $270 billion in revenues and profits of $125–150 billion by 2040 (Smart Mobility Team, 2018).

The future mobility is people-centric, software-defined, connected, and electric. With people-centric mobility, quality of life in the cities will be improved. Software algorithms play crucial roles in enabling advanced assisted driving and automated driving vehicles, shared mobility services, Mobility-as-a-Service, mobility on demand, and seamless integrated mobility. Automated mobility will reduce injuries and fatalities, improve access to mobility for those who currently cannot drive due to age or disability, and create new business models such as passenger economy. Shared mobility relies on sharing economy business model that replaces ownership with usership. Connected mobility creates new data-rich environments and is an enabler for many applications and services that will make our roads safer, less congested, and eco-friendlier. Electrification is an enabler for zero emission and sustainable mobility. However, the widespread deployment and the societal acceptance of smart mobility technologies like automated driving will depend not only on the maturity of the technology but also on the availability of a well-developed governance framework and the proper city planning to accommodate these evolving technologies. This means that smart mobility depends on a triad of complementary factors, namely, technology, governance, and city planning, as illustrated in Figure 2-1.

The three components of this smart mobility triad are not separate components as they impact each other. The following sections shed some light on these three components.

2.1. Smart Mobility Governance

The creation of a comprehensive and effective governance framework for smart mobility services is challenging and is a moving target as this framework should embrace existing and emerging technologies and encourage innovation while ensuring societal and environmental risks are identified and carefully managed.

There is an old parable about an elephant and a group of blind men in a room. None of these men had come across an elephant before. After each having touched a different part of the elephant in the room, the blind men are asked to describe the elephant from what they have just experienced. The blind man who felt the leg declares, "It's like a tree or a pillar"; the one who felt the tail declares with confidence, "It's like a rope"; the one who felt the trunk says, "It's like a snake or a hose"; the one who felt the ear declares without doubt, "It's like a soft blanket"; and the one who felt the belly declares knowingly, "It's a wall." So each blind man senses the elephant from his particular point of view and comes up with a different conclusion. Likewise, smart mobility governance regulations should be developed taking into consideration different opinions and concerns from multiple stakeholders. These stakeholders include policy makers, city authorities, environment activists, insurance companies, equipment/mobility platform manufacturers, smart mobility service providers, drivers, pedestrians, cyclists, public transit users, ridesharing users, micromobility users, and other users of smart mobility services. None of these stakeholders have the full picture about what is needed to regulate the smart mobility services and how to balance different needs and demands.

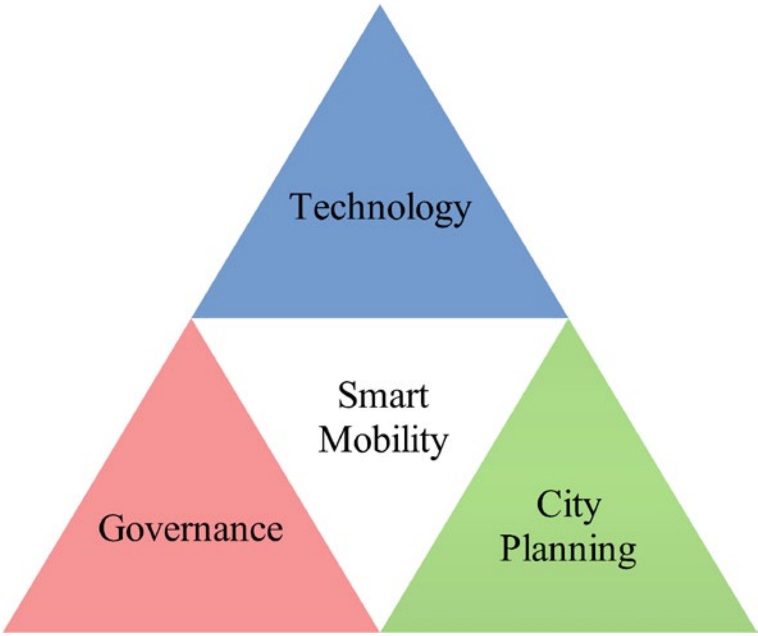

Figure 2-1. Smart Mobility Triad

The legal and regulatory environment around several smart mobility technologies is still unclear and not well developed especially when it comes to safety verification and validation, mixed traffic management (nonautomated driving with automated driving vehicles), data privacy, and liability. Considering safety as the top priority, several safety standards and safety performance assessment programs are available and keep evolving. For example, to deal with possible hazards caused by malfunctioning behavior of E/E safety-related systems, the ISO 26262 Functional Safety standard was introduced. The system faults can be deterministic and attributable to causes or unpredictable and probabilistic in case of random hardware failure. Failure Modes and Effects Analysis (FMEA) is a structured approach commonly used by automakers to discover potential failures that may exist within the design of a vehicle or a process.

The European New Car Assessment Programme (Euro NCAP)[2] is commonly used for car safety performance assessment. Safety of the Intended Functionality (SOTIF or ISO/PAS 21448) (ISO, 2019) was developed to address new safety challenges that assisted driving and automated driving vehicle software developers are facing. SOTIF addresses performance limitations in sensors, algorithms, and actuators. SOTIF provides guidance on design, verification, and validation measures. Several features can potentially use SOTIF such as longitudinal control, lateral assist, lane changes, hand-free driving, auto parking, and auto-summon. Inclement conditions are also challenging for automated driving vehicles for several reasons. Snow and rain can obscure and confuse sensors, hide markings on the road, and make a vehicle perform differently. The ultimate objective of SOTIF is to limit the number of unknown unsafe states that the automated driving system (ADS) could be in. Moreover, Concepts of Design Assurance for Neural Networks (CoDANN) was developed by the European Union Aviation Safety Agency (EASA) (Cluzeau et al., 2020) as a way to verify and validate data-driven models for safety-critical applications. For more information about verification and validation methods for SAE level 3–4 automated driving (conditional/high automation), the reader can refer to the "Safety First for Automated Driving (SaFAD)" white paper published by 11 major stakeholders in the automotive and automated driving industry, including Audi, Baidu, BMW, Intel, Daimler, and VW (Wood et al., 2019). The Safe Drive Initiative (SafeDI) developed by the World Economic Forum (WEF) seeks to bridge the gap between the industry's expertise in AV safety and the regulators' desire to set policy that safeguards AV deployment (World Economic Forum (WEF), 2020). Various types of alliances, coalitions, standards bodies, and partnerships available for industry decision-makers related to autonomous driving are highlighted in the AV Governance Ecosystem report (World Economic Forum (WEF), 2021)

[2] www.euroncap.com/en

published by Autonomous and the WEF. The Autonomous[3] global community publishes updated information about different initiatives and coalitions for automotive and autonomous mobility industry decision-makers.

Liability aspects of smart mobility technologies such as automated driving systems (ADSs) are still uncertain and not fully defined. Different forms of liability should be discussed such as owner liability, manufacturer/supplier liability, insurer liability, and intelligent transportation system (ITS) liability. Owners would be liable for any accident if the automated driving vehicle is not insured. In case of product failure, the civil liability will be imposed on the producers, own-branders, and importers of defective products. The insurer is directly liable according to terms and conditions of insurance coverage. The ITS owner and manager may be also liable if the accident occurs due to infrastructure failure.

Generally speaking, the legal landscape of autonomous vehicles is still evolving. In recent years, several regulatory and legislative actions focused on automated driving systems have been initiated in different courtiers such as the H.R.3388—SELF DRIVE Act in the United States, UK Code of Practice for Automated Vehicle Trialling, Autonomous Vehicle Bill in Germany, French legislative framework for autonomous cars, and EU Standard for Safety for the Evaluation of Autonomous Products (UL-4600). For example, the SELF DRIVE Act blocks states from banning self-driving vehicles, grants exemptions to existing safety standards for a company's first 100,000 vehicles, and requires manufacturers to develop plans to thwart cyber-attacks on digitally run vehicles. Germany has recently approved the world's first legal framework for integrating autonomous vehicles in regular traffic. The adopted legislation will change traffic regulations to allow driverless vehicles on public roads by 2022, laying out a path for companies to deploy robotaxis and delivery services in the country at scale. According to NHTSA (National Highway Traffic Safety Administration and others, 2017), public trust and confidence in the evolution of ADSs has the potential to advance or inhibit the testing and deployment of ADSs on public roadways. This also applies to other disruptive smart mobility systems and services such as air taxis and autonomous cargo ships. For example, the quickly evolving urban air mobility (UAM) platforms for people and cargo transportation require a regulatory environment to address different aspects of UAM such as safety, privacy, noise pollution, visual disruption, and wildlife impact and compliance with different civil aviation standards and recommended practices such as ICAO SARPs, FAA FARs, JAA, EASA, and so on. The Federal Aviation Administration (FAA) is now one step closer to the much anticipated "Unmanned Aircraft System Traffic Management (UTM)" ecosystem. UTM will identify services, roles, and responsibilities, information architecture, data exchange protocols, software functions, infrastructure, and performance requirements for enabling the management

[3]www.the-autonomous.com/

of low-altitude uncontrolled drone operations. UTM is a separate but complementary framework to the FAA's Air Traffic Management (ATM) system. Changing maritime laws and regulations is still a challenge against accommodating the use of autonomous ships for people mobility and cargo delivery. Although the regulations in national waters can be adapted quicker, changing international regulations to facilities the introduction of autonomous ships in international waters will take some time to address several aspects of security, safety and liability. Governance and regulatory processes that support, or sometimes prevent, the development and implementation of smart mobility solutions (shared, automated, electric, integrated) are highlighted in (Finger and Audouin, 2018).

2.2. City Planning

Just as the arrival of the first automobiles fundamentally changed our society in the early 1900s, smart mobility systems will trigger evolutionary and revolutionary changes in the city planning. These changes will include, but are not limited to, the following:

- Replanning transport corridors and city streets to accommodate more pedestrians, cyclists, riders in shared transportation, and less cars
- Setting up walking routes and cycling lanes for active, soft, and inclusive mobility
- Enabling bicycle highways (a.k.a. bicycle freeways or superhighways) that offer a direct route with few intersection stops
- Establishing emergency safe spots in the city for automated driving vehicles in case remote/on-site human intervention is needed
- Installing harbors as part of the highways to be used in case of faulty autonomous vehicles or unplanned road events
- Upgrading city infrastructure to provide real-time traffic updates, traffic accidents/incidents, social/sport event events that may affect the traffic, work zones and any temporary changes to the roadworks such as road closure and lane change. Safety critical information can be gathered by infrastructure-mounted sensors and transmitted to the connected vehicles
- Installing connected mobility infrastructure like ITS, smart intersections, and smart pavement

- Enabling highly visible and readable signages such as pedestrian crossings (e.g., pelican, puffin, toucan, and zebra crossings), school zone, railway crossing, yield, road edges, curves, speed limits and parking to adopt assisted and automated driving vehicles. In this context, EU Member States investigate unifying safety critical road signs to aid with recognition by assisted and automated driving vehicles
- Replacing road signage with digital and connected road signage to deal with a problem like road infrastructure deterioration that may impact the operation of the automated driving systems
- Creating new pedestrian unsignalized crosswalks to avoid a crosswalk chicken game
- Upgrading engineering countermeasures for speed management such as horizontal deflection (e.g., roundabouts, lateral shifts, chicanes), vertical deflection (e.g., speed humps, raised crosswalks and cushions) and street width reduction (e.g., on-street parking, road diets and corner extensions)
- Installing smart parcel lockers for last-mile delivery
- Allocating stacks and racks/pickup and drop-off points for mobility on demand systems
- Setting up stations for micromobility
- Hosting more electric vehicle charging stations, wireless/ cordless charging pads and charging roads that enable charging while driving
- Assigning air taxi takeoff and landing locations
- Enabling smart parking to allow continuous monitoring of the parking space and automate several operational processes such as detection of parking availability and digital payment. These smart parking systems need to be upgraded to accommodate emerging technologies such as Automated-Valet-Parking (AVP) and automated driving electric vehicle parking. Examples of these changes include optimized layout, charging points/wireless charging pads, communication infrastructure and drop-off and retrieval zones
- Finally, with the emerging heavy truck platooning technology, bridge operational constraints should be considered during fleet management. Bridge design standards need to be revised as well

2.3. Smart Mobility Technology

In his book *Profiles of the Future: An Inquiry into the Limits of the Possible* (Clarke, 2013), the English science fiction writer and inventor Arthur Clarke formulated his famous Three Laws, of which the third law is the best-known and most widely cited: "any sufficiently advanced technology is indistinguishable from magic." Connected vehicle technology is the magic that creates new data-rich environments and enables many applications and services that will make our roads safer, less congested, and eco-friendlier. Shared mobility technology is the magic that replaces ownership with usership. Mobility-as-a-Service (MaaS), mobility on demand (MOD), and seamless integrated mobility systems (SIMS) are the magic that enables seamless mobility as the neo-liberalization of people and goods transportation. Self-driving technology is the magic that will dramatically reduce injuries and fatalities, improve access to mobility for those who currently cannot drive due to age or disability, and open the doors to passenger economy. 3D mobility is the magic that moves us from restricted mobility in two-dimensional streets that enables only 2-DOF (degree of freedom) (lateral and longitudinal motion) to 3-DOF mobility (lateral, longitudinal, and vertical motion) or more accurately 6-DOF mobility (lateral, longitudinal, vertical, roll, pitch, and yaw) considering the rotational movements of the aerial platform. Zero-emission hyperloop technology is the magic that will take you from Los Angeles to San Francisco in just 35 minutes instead of 2.5 hours in a high-speed rail system. Electrification is the magic that will enable net zero emission and sustainable mobility in the near future.

The technological aspects of smart mobility can be explained in terms of foundational technologies, technology enablers, and disruptors as illustrated in Figure 2-2. The lists shown in this figure are not comprehensive of today's foundational technologies, enabler technologies, and disruptors that keep changing dynamically. However, the mentioned technologies are the core building blocks of the existing and possibly emerging smart mobility systems and services. Moreover, other hardware-related technologies like embedded systems, sensors, actuators, body design, displays, and other technologies such as E/E architecture, testing, verification, validation, and cybersecurity are of equal importance but are not covered in this book.

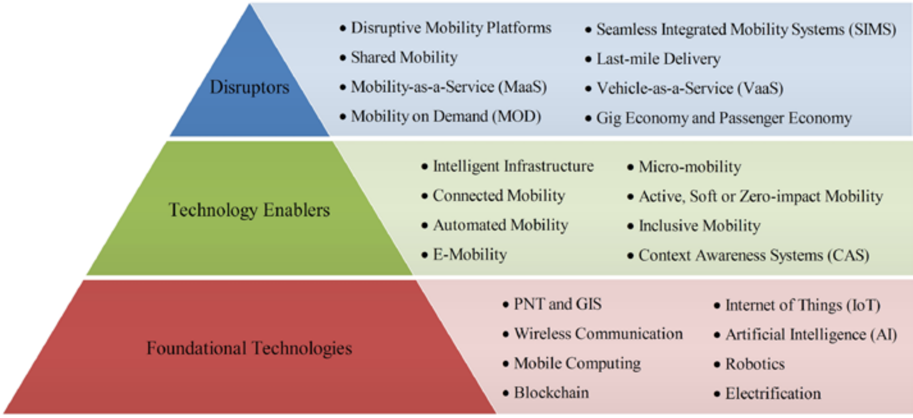

Figure 2-2. Smart Mobility: Foundational Technologies, Technology Enablers, and Disruptors

The following chapters focus on the technological aspects of smart mobility systems and services describing their foundational technologies, technology enablers, and disruptors. Foundational technologies covered in this book include Position, Navigation, and Timing (PNT), Geographic Information System (GIS), wireless communication, mobile cloud computing, blockchain, Internet of Things (IoT), Artificial Intelligence (AI), robotics, and electrification. PNT technologies endow smart mobility systems with the ability to localize stationary and mobile assets within the system, guide the navigation of the mobile assets, and maintain accurate and precise timing. GIS provides the necessary geographical information to abstract the work environments. Wireless communication enables the transmission and exchange of real-time data with high reliability within the smart mobility system. Mobile computing enables authorized end users and mobile assets to gain a speedy access to data, information, and computation from wherever they are. Based on the concept of distributed computing, blockchain technology enables several services such as authentication, access control, and fast payment and has the potential to reshape smart mobility systems and services. IoT technologies enable connecting any stationary or mobile asset within the smart mobility system to the Internet and facilitate data sharing for monitoring, control, and optimization. AI is a foundational technology and a driving force behind several existing and emerging smart mobility systems and services. Robotics is seen as a foundational technology given the fact that several smart mobility technologies began to emerge from robotics research labs and are based on advances in robotics fields in terms of mechanical design, locomotion systems, perception, planning, control, navigation, and coordination algorithms. Electrification is also another foundational technology for decarbonized sustainable mobility. More details about these foundational technologies are provided in Chapter 3.

In the context of smart mobility, the book covers several technology enablers such as intelligent infrastructure, connected mobility, automated mobility, e-mobility, micromobility, active/soft mobility, inclusive mobility, and Context Awareness Systems (CAS). Supportive intelligent infrastructure includes intelligent transportation systems, smart pavement, smart intersections, high-quality cycling infrastructure such as cycle highways (a.k.a. bicycle freeways or superhighways), smart parking, and charging infrastructure. Connected mobility is a key enabler for real-time navigation and routing, traffic information, safety warnings, accident avoidance, advanced driver assistance systems (ADAS), and automated driving systems (ADSs). Automated driving enables the radical reduction of injuries and fatalities usually caused by human driver errors. E-mobility enables and powers different environment-friendly mobility platforms such as e-cars, e-bikes, e-scooters, eVTOL, and electric shuttles/commuters. Micromobility platforms enable first-/last-mile affordable and sustainable mobility. Active, soft, or zero-impact mobility opens doors to a healthy, cheap, fun, and environmentally friendly option for first-/last-mile urban mobility. Mobility aids enable inclusive mobility for the elderly and physically challenged. Last but not least, situational awareness is an enabler for context-aware mobility systems and services able to adapt following specific contextual information. More details about these technology enablers are provided in Chapter 4.

Mobility disruptors described in the book include disruptive mobility modes, shared mobility, Mobility-as-a-Service (MaaS), mobility on demand (MOD), seamless integrated mobility systems (SIMS), last-mile delivery, Vehicle-as-a-Service (VaaS), gig economy, and passenger economy. Disruptive mobility platforms for people mobility and goods delivery include autonomous ground vehicles (e.g., self-driving shuttles (SDSs), autonomous wheelchairs, autonomous carts, and autonomous robot valets), urban air mobility (e.g., air taxis, air metro, and last-mile delivery drones), and marine vehicles (water taxis, water buses, and autonomous boats/ships). Automated people movers, hyperloops, and urbanloops are other examples of disruptive mobility platforms. Vehicle sharing, peer-to-peer sharing, demand-responsive transit (DRT), ridesharing, ridehailing, ridesourcing, and ridesplitting services are examples of shared mobility services. MaaS, mobility on demand, and seamless integrated mobility systems facilitate easy-to-access and seamless mobility. Modern last-mile delivery services focus on movement of goods from a warehouse or a distribution store to the final delivery destination in the fastest, most flexible, and transparent way possible. In the era of disruptive innovation, a mobility platform or a vehicle can be seen as a service to enable sharing and monetizing the unused computational and/or networking resources in the vehicle and/or the huge amount of collected data. Several smart mobility services can be enabled based on gig economy and passenger economy especially in the era of automated driving vehicles where vehicles can be repurposed for different leisure, business, or healthcare uses. More details about these disruptors are provided in Chapter 5.

CHAPTER

3

Smart Mobility: Foundational Technologies

Foundational technologies represent smart mobility's building blocks that can be used to effectively develop and underpin important new products and services. Position, Navigation, and Timing (PNT), Geographic Information System (GIS), wireless communication, mobile cloud computing, blockchain, Internet of Things (IoT), Artificial Intelligence (AI), robotics, and electrification are discussed in this chapter as examples of foundational technologies for smart mobility systems and services.

3.1. PNT and GIS

Positioning, Navigation, and Timing (PNT) is defined by the Department of Transportation (DOT) as a combination of three distinct, constituent capabilities (Wallischeck et al., 2016):

A. Khamis, *Smart Mobility*, https://doi.org/10.1007/978-1-4842-7101-8_3

- **Positioning** is the ability to accurately and precisely determine one's location and orientation two-dimensionally (or three-dimensionally when required) referenced to a standard geodetic system (such as the World Geodetic System 1984, or WGS84).
- **Navigation** is the ability to determine the current and desired position (relative or absolute) and apply corrections to course, orientation, and speed to attain a desired position anywhere around the world, from subsurface to surface and from surface to space.
- **Timing** is the ability to acquire and maintain accurate and precise time from a standard (Coordinated Universal Time, or UTC), anywhere in the world and within user-defined timeliness parameters. Timing also includes time transfer.

Generally speaking, vehicle localization can be classified based on the work environment of the vehicle into indoor localization and outdoor localization. Indoor localization is the process of accurately estimating the position and orientation of a vehicle moving inside a building's environment (Mautz, 2012). The level of complexity tackled in this process depends mainly on characteristics of the environment. Indoor environments can either be classified into structured or unstructured, fully observable or partially observable, or even static or dynamic. Indoor localization in an unstructured partially observable dynamic environment is considered as a challenging process. This process starts by observing the environment using different sensors such as radio wave–based sensors, magnetic sensors, acoustic sensors, or cameras. The collected data is then further processed for filtration and postprocessing through utilizing various positioning methods to accurately determine the location of the vehicle within the vicinity of its environment. Examples of these positioning methods include Cell of Origin (CoO)/Proximity Detection/Connectivity-Based Positioning, Centroid Determination, lateration/trilateration/multilateration, polar point method/range-bearing positioning, fingerprinting/scene analysis/pattern matching, and dead reckoning. These different positioning methods differ in their levels of accuracy as well as coverage. According to the desired level of accuracy of the target application, the appropriate corresponding localization technology can be selected. The relative accuracy and coverage of different indoor localization technologies are described in (Mautz, 2012).

Apart from the natural features of the outdoor environments as being large scale, unstructured by nature, being partially observable, as well as dynamic—compared to indoor localization—outdoor localization is a more challenging process than indoor localization. This is mainly due to the lack of the ability to control the environment and the limited predictability of dynamic outdoor environments.

The outdoor localization techniques can be classified into three main categories: relative localization, global localization, and hybrid localization techniques. In relative localization techniques, the main objective is to accurately evaluate both the position and orientation using the information provided through the different onboard sensors (e.g., encoders, gyroscopes, accelerometers, etc.). In these techniques, the position and orientation are measured with respect to an initially known pose from which the vehicle started its operation. These techniques generally inhibit several uncertainties as the error that is produced during the measurement keeps accumulating over time. This leads to a growing error ellipse that may cause drifting of the measured readings from the actual pose over time. Dead reckoning (Brossard et al., 2020), inertial navigation (Woodman, 2007), and visual odometry (Maimone et al., 2007) are examples of relative localization techniques. Unlike relative localization techniques, global localization techniques determine the position and orientation of the vehicle with respect to a global reference frame. Examples of global localization techniques include ground-based RF systems, active RFID technology, real-time locating techniques, Global Positioning Systems (GPSs), submeter GPS techniques (e.g., Satellite-Based Augmentation System, precise point positioning (PPP), and Real-Time Kinematics (RTK)), Real-Time Locating Systems (e.g., Ultra-wide Band or UWB RTLS), and hybrid techniques (e.g., GPS and UWB). The most popular technique is GPS (Samama, 2008), which is based on satellite signals to determine the absolute position (longitude, latitude, and altitude) of the vehicle on Earth. GPS provides users with space-based PNT services. It is undeniable that technological advances, and wide-scale availability of PNT/GPS technology over the past several decades, have enabled significant innovations in the mobility domain. These innovations have improved the safety, efficiency, and reliability of all modes of transportation and will help in enabling another transformational shift in transportation—toward greater automation (Bisnath, 2019). These technologies are critical to smart mobility systems, which rely on highly accurate and reliable positioning, navigation, and timing information. GPS provides position on Earth's surface and above with different levels of precision ranging from 3–10 meters down to the accuracy of centimeters, depending on the accuracy of the GPS tracker used. Aside from GPS, other global navigation satellite systems (GNSSs) include European Union's Galileo, Russia's Global Navigation Satellite System (GLONASS), and China's BeiDou Navigation Satellite System (BDS). Galileo is similar to GPS but offers new services and additional positioning and timing accuracy and reliability. It is the only system designed for civilian applications and managed by civil authorities. Hybrid localization techniques such as precise point positioning (PPP) GPS and Real-Time Kinematics (RTK) GPS are commonly used to improve the precision of GPS. PPP stands out as an optimal approach for providing centimeter-level error positioning using GNSS constellations. PPP processes measurements from a single-user receiver, using detailed physical models and corrections, and precise GNSS orbit and clock products computed beforehand. PPP differs from other precise positioning approaches like RTK in that no reference stations are needed in the vicinity of the vehicle. Another advantage is that since the GNSS orbit and clock products are by nature global, the PPP solutions are also global. For example, Trimble RTX is an advanced PPP technology that provides real-time, centimeter-level positions. RTK satellite navigation is a technique based on the use of carrier phase measurements of GPS, GLONASS, and/or Galileo signals where a single reference station provides real-time corrections, providing up to centimeter-level accuracy. RTK correction signals are typically transmitted by a base station by means of a UHF radio receiver/transmitter or by an NTRIP server (via a GSM network) if a CORS network is available in the area. The Network-RTK Positioning for Automated Driving (NPAD) project is described in (Nord et al., 2021). The main drawback of RTK technology is the short transmission range of low-powered systems caused by obstacles located in the path between a base station and a mobile receiver. Another drawback is signal interference, which can reduce transmission range and cause poor signal quality.

WiFi-based positioning can handle the traditional GPS shortcomings in metropolitan areas. In this case, WiFi-based positioning can be explored through both trilateration and fingerprinting techniques as relying only on trilateration would not be a suitable candidate due to the need for at least three reference points with direct lines of sight to localize the vehicle in a 2D plane, which are not always available in areas like urban canyons. WiFi positioning estimates from both trilateration and fingerprinting can be cotrained with a GPS/smartphone position model. Other emerging positioning technologies include 5G/3GPP (e.g., R16 NR Positioning), cellular V2X (vehicle-to-anything) (e.g., R16 NR V2V/V2I), and Visual Positioning System (VPS). VPS or vision-based map matching is a potential positioning modality. In VPS, the position of the vehicle is estimated based on recognizing natural landmarks and matching them with the known area map.

Geographic Information System (GIS) is an information system for input, storage, manipulation, and output of geographical information. GIS plays a crucial role in existing and emerging mobility systems. Nowadays, several Internet-based mapping technologies provide free satellite imagery, aerial photos, and topographic data for most of Earth's land surface, resulting in increased availability of mapping technology. Examples include Google Earth, Google Maps, OpenStreetMap, ArcGIS, QGIS, 2GIS, Bing Maps, HERE WeGo, and MAPS.ME. Other mapping services such as AccuTerra focus on providing mapping for recreation from US Geological Survey (USGS) topographic map series, national parks, national forests, and Bureau of Land Management data.

High-definition (HD) maps can be constructed using different approaches to provide extremely high-precision information at a centimeter level for smart mobility platforms such as automated driving vehicles. Examples of this information include lane boundaries, intersections, crosswalks, parking spots, stop signs, traffic lights, and so on. When we are creating HD maps of a city, we are creating the digital infrastructure of a city's road network (Vardhan, 2017). According to Lyft (Chellapilla, 2018), a HD map is organized into five layers, namely, a base map (standard-definition map), a geometric map that contains 3D information of the world, a semantic map built on the geometric map layer by adding semantic objects, map priors containing derived information about dynamic elements and also human driving behavior, and the read/write real-time knowledge layer. Different types of sensors such as GPS, cameras, radar, and LiDAR sensors are used and fused to create these HD maps.

Combining 5G with PNT, GIS, HD mapping techniques, and traffic density data will enable several smart mobility applications that require fast data transmission speed, low network latency, precise location, navigation, timing and mapping services, and real-time traffic data. Application examples include efficient routing and rerouting, mobile asset tracking, location-aware services, Mobility-as-a-Service, mobility on demand, and seamless integrated mobility services to name just a few. For instance, a navigation app like Google Maps encompasses the following components:

- **Map Encoding Algorithms:** Are spatial indexing algorithms and algorithms of computational geometry to organize the map data and retrieve it efficiently. Directed graphs and contraction hierarchies are commonly used to represent the map. Road classification hierarchy or road hierarchy is a scheme for categorizing roads into groups based on a number of factors such as usage, location, surface type, capacity, and so on.
- **Map Drawing Algorithms:** To draw maps (e.g., project latitude and longitude coordinates; fill the polygons; place names for streets, cities, businesses, and parks; and so on).
- **Query Understanding Algorithms:** Understand queries from users. These queries can be typed or spoken. Search location by image is also a possibility. Natural language processing, speech recognition, and machine vision are employed by the query understanding algorithms.
- **GPS Signal Processing Algorithms:** To improve accuracy and handle different imperfection aspects of low-cost GPS such as uncertainty and ambiguity.

- **Geocoding Algorithms:** To convert addresses to points (or polygons) on a map using a geographic coordinate system. A geographic coordinate system is a coordinate system that enables every location on Earth to be specified by a set of numbers, letters, or symbols (Crossley, 1999). Common map projections to assign coordinates to locations on the surface of Earth include latitude/longitude coordinates, the Universal Transverse Mercator (UTM), the Military Grid Reference System (MGRS), the US National Grid (USNG), the Global Area Reference System (GARS), and the World Geographic Reference System (GEOREF). What3words (W3W)[1] is a human-readable geocode system for the communication of locations with a resolution of three meters. Similarly, Plus codes created based on Google's Open Location Code (OLC) geocode system also provide geo-labels that are based on latitude and longitude and displayed as numbers and letters. These geo-labels like W3W and Plus codes can be used to label locations without formal addresses given the fact that half of the world's urban population lives on an unnamed street.
- **Routing Algorithms:** To find the optimal route between the current location and the destination (shortest or fastest path in large time-dependent road networks). Mobile apps like Waze, Apple Maps, and Google Maps are commonly used as navigation apps that provide optimal or suboptimal routes. However, more advanced versions of these apps are needed to include additional information such as capacity of residential streets and dynamic events that may compromise safety or result in congestion (Macfarlane, 2019). Routing is usually treated as a graph search problem. A graph is a mathematical way to represent the road network. The graph nodes represent intersections, and the edges represent the roads. A route is a sequence of edges connecting the origin node to the destination node. Dijkstra's, A-start, and contraction hierarchy algorithms are commonly used to solve routing problems as illustrated in Figure 3-1.

[1] https://what3words.com/

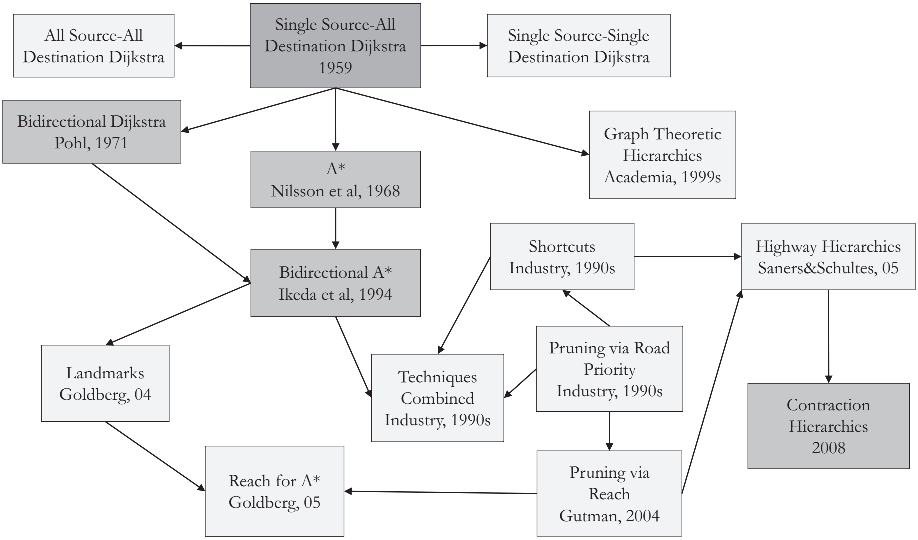

Figure 3-1. Examples of Routing Algorithms

These graph search algorithms and others are available for routing problems in this GitHub repo[2] developed by me as part of the course I teach in The Edward S. Rogers Sr. Department of Electrical and Computer Engineering (ECE) at the University of Toronto, Canada.

Important A reduction of one mile per driver per day translates to savings of up to $50 million a year (Jack Levis, Director of Process Management of UPS).

- **Routes Based on Transportation Mode:** Different routes are calculated based on the available transportation modes (driving, motorcycle, cycling, transit, walking, ride services).
- **Reverse Geocoding Algorithms:** To perform reverse geocoding, converting points to addresses using point-in-polygon algorithms.
- **Guidance:** To provide guidance during route execution using graphics and audible alerts and text-to-speech synthesis or a speech assistant.

[2] https://github.com/SmartMobilityAlgorithms

- **Off-Route Detection and Rerouting:** To detect when the driver has gone off the route and needs a new route.
- **Points of Interest:** Malls, restaurants, parking spaces, and so on are highlighted in the vicinity of the current location.
- **Handling Differences:** In terms of lighting condition, for example, to help travelers navigate via well-lit streets or avoid dark streets while walking using the street lighting layer of Google Maps. Another example is to switch measuring units from mile to km or vice versa or change rules for using roads when crossing the border between countries like United States-Canada or United States-Mexico.

3.2. Wireless Communication

Over the past decade, the demand for wireless technologies has been absolutely exploding, and cellular and personal communications have become the fastest-growing segments of the telecommunications services (Chen, 1998). Wireless communication facilitates the transmission and exchange of real-time data with high reliability and ensures smooth integration between mobility platforms and their environments. Many efforts have been carried out by researchers to enable wireless vehicular communication in dense, dynamic, and harsh weather environments (Siegel et al., 2018; Bey and Tewolde, 2019). Latency, power consumption requirements, scalability, and cost are critical factors that affect wireless communication especially in the case of electric vehicles (EVs).

Wireless communication technologies for smart mobility systems mainly include Dedicated Short-Range Communications (DSRCs) and Cellular V2X (C-V2X) communication. Moreover, more ongoing research has been conducted about whether combining both technologies will result in a more prosperous future for mobility systems:

- **DSRC** (Shukla et al., 2020): Is based on IEEE 802.11p to allow continuous, low-latency, and secure data exchanges between moving vehicles (V2V) and between vehicles and infrastructure or mobile devices (V2X).
- **C-V2X** (Abou-Zeid et al., 2019): Is based on single-carrier frequency division multiple access (SCFDMA) in the physical layer for higher data rates and extended ranges compared to DSRC. Although some see DSRC as an obsolete technology compared to LTE- or 5G-supported

C-V2X, today's LTE wireless communications cannot adequately support communications for crash-imminent vehicle safety applications due to high latency. The promising capabilities of 5G will handle this limitation, but it may take a while to widely deploy 5G infrastructure.

- **Hybrid Architecture**: Interworking between DSRC and cellular technology that forms a hybrid solution is considered promising, as it utilizes the benefits of both enabling technologies. For instance, in situations where transmitted data between vehicles are shattered and V2V multihop communication fails, cellular technologies may perform as a backup solution to relay transmitted information. Also, vehicles may reconnect to the Internet access network of the cellular technology in case of Internet connection loss with the RSUs. Figure 3-2 illustrates some safety applications where the integration between DSRC and cellular technology will be beneficial.

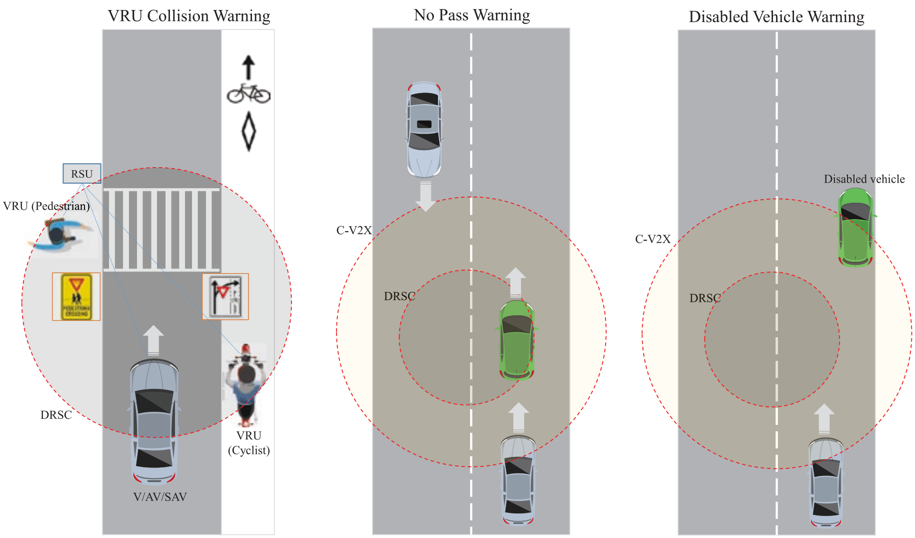

Figure 3-2. VRU (Vulnerable Road User) Collision Warning, No Pass Warning, and Disabled Vehicle Warning

On November 18, 2020, the Federal Communications Commission (FCC) in the United States has reallocated the 5.9 GHz "Safety Spectrum" long reserved for the transportation sector to WiFi and C-V2X. The ruling effectively eliminates the future for WiFi-based DSRC and locks in the advancing alternative, C-V2X.

Communication satellites such as Geosynchronous Equatorial and Geostationary Orbits (GEO/GSO), Medium-Earth Orbit (MEO), and Low-Earth Orbit (LEO) (Yang, 2019) can provide low-cost global connectivity that can be used in smart mobility systems. Several companies like SpaceX, OneWeb, and even Facebook are investing in satellite constellations that will provide affordable consumer Internet to the entire planet. Amazon is also working on satellite communication for logistics. Different automakers such as Tesla, Toyota, and Geely have programs to own satellite networks and to incorporate satellite communication into their vehicles. A hybrid approach would also be an option where terrestrial cellular communication can be combined with satellite communication (GEO or LEO) to deal with problems like out of coverage and reliability. Possible applications of this hybrid communication system include content streaming, gaming, fleet management, over-the-air (OTA) updates, emergency notification, precise positioning, and autonomous vehicles' mission-critical applications such as tele-assistance or teleoperation (e.g., bring a faulty autonomous vehicle to a safe harbor or allow the autonomous vehicle to violate a traffic rule in a specific situation where the autonomous vehicle gets stuck).

3.3. Mobile Computing

Mobile computing is the set of information technologies, products, services, and operational strategies and procedures that enable authorized end users and mobile assets to gain access to data, information, and computation from wherever they are. Based on the proximity of data sources, storage, and computational units, mobile computing can be classified into mobile cloud computing (MCC), mobile fog computing (MFC), and mobile edge computing (MEC) (see Figure 3-3).

Mobile cloud computing (MCC) is defined as

> *a rich mobile computing technology that leverages unified elastic resources of varied clouds (private or public) and network technologies toward unrestricted functionality, storage, and mobility to serve a multitude of mobile devices anywhere, anytime through the channel of Ethernet or Internet regardless of heterogeneous environments and platforms based on the pay-as-you-use principle.*
>
> —Sanaei et al., 2013

MCC as the combination of cloud computing and mobile computing is being embraced by researchers and practitioners as an exciting new way to extend the capabilities of mobile devices and mobile platforms, which has the potential for profound impacts on the business environment and people's daily life (Leung et al., 2013).

Mobile fog computing (MFC) (An et al., 2018) and mobile edge computing (MEC) (Li et al., 2016) are two emerging paradigms used to solve some issues in cloud computing related to latency, bandwidth, privacy, and security. Both MFC and MEC bring computation and storage closer to where the data is generated enabling mobile users/mobility platforms to offload partial or complete computation-intensive and time-constraint tasks to nearby or local servers for computing. This allows ultralow latency, better bandwidth utilization, faster insights and actions, and higher scalability as a result of reducing the data to be sent to centralized data centers or to the cloud and performing the computation on fog or on edge. Privacy and security are additional benefits of MFC and MEC in the context of smart mobility where MFC can be used to manage a fleet of autonomous vehicles in a certain geo-fenced area and MEC can be used to run AI-based modules in each vehicle for perception, planning, control, learning, and adaptation. Figure 3-3 illustrates an example in the context of machine learning–based service deployment.

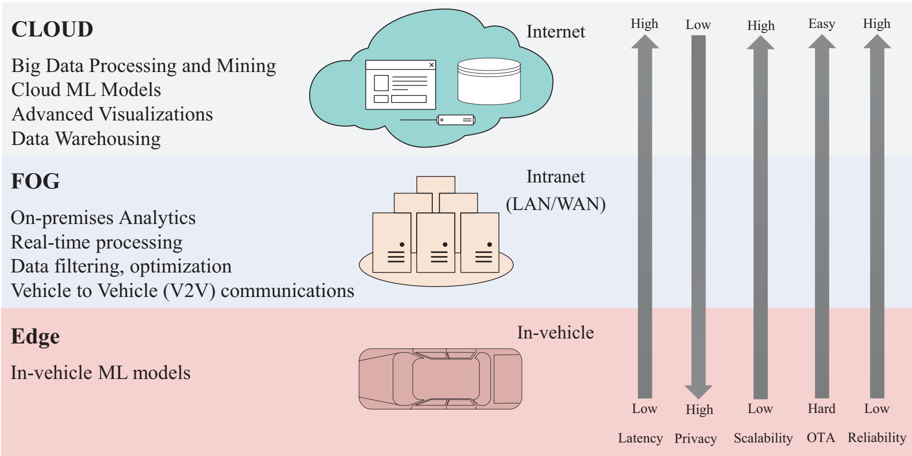

Figure 3-3. Mobile Computing Deployment Architectures

Note The advent of ubiquitous mobile computing technologies has catalyzed changes in the transportation industry.

Mobile computing is a foundational technology behind several disruptive mobility services such as app-based transportation network companies (TNCs), Anything-as-a-Service (XaaS), Mobility-as-a-Service (MaaS), Vehicle-as-a-Service (VaaS), click and collect last-mile delivery service, and mobile cloud sensing. For example, several mobile cloud sensing applications can be developed based on mobile computing such as the following (Han et al., 2015):

- **Individual Sensing Apps**: Such as self-exercise management and daily activity recording for active mobility
- **Group Sensing Apps**: Such as road condition monitoring, cooperative mapping, and autonomous garbage collection
- **Community Sensing Apps**: Such as traffic monitoring and pollution monitoring
- **Opportunistic Sensing Apps**: With no user interaction where the sensing activity can last for a long term but the results depend on a stable sensing environment without much disturbance
- **Participatory Sensing Apps**: Where users have to be persuaded to take part in the sensing, with the incentives being money, common interest, and responsibility

3.4. Blockchain

The concept of distributed computing has been around since 1990. Blockchain was invented in 2009 to serve as the public transaction ledger of the cryptocurrency Bitcoin (Staff, 2016). Satoshi Nakamoto created Bitcoin and introduced the concept of a blockchain to create a decentralized ledger maintained by an anonymous consensus as the first blockchain database. The deployment of cryptocurrency in applications related to cash started in 2011, followed by introducing currency transfer and digital payment systems in 2012. Smart contracts started to evolve in 2014, and permissioned blockchain network solutions appeared in 2015. Starting from 2016, blockchain starts to penetrate in different industries.

Based on a peer-to-peer (P2P) topology, blockchain is a distributed ledger technology (DLT) that provides a credible and transparent environment that allows data to be stored globally on thousands of servers and facilitates access to this data (Mearian, 2019). Blockchain is a distributed database of records or a public ledger of all transactions or digital events that have been executed and shared among participating parties (Crosby et al., 2016). A ledger is essentially a database of transactions. This technology is a new organizing paradigm for the discovery, valuation, and transfer of all quanta (discrete units) of an asset. This asset can be hard assets (physical property, homes, cars) or intangible assets (votes, ideas, reputation, intention, health data, information, etc.) (Swan, 2015). In the context of smart mobility, physical assets can be mobility platforms like cars, bikes, scooters, public transit, automated people movers, or hyperloops. Digital assets can be an access code to a shared vehicle or a smart locker or a digital twin of a smart mobility platform or any other physical objects such as a spare part or a charging station. These assets can be registered with a unique identifier and tracked, controlled, and exchanged on the blockchain. Data transparency, security, asset management, and smart contracts are listed as key and differentiating features of blockchain technology (Heutger et al., 2018):

- **Data Transparency:** Blockchain technology includes mechanisms to ensure stored records are accurate, tamper-evident, and from a verifiable source.
- **Security:** Individual transactions and messages are cryptographically signed. This ensures essential security and effective risk management to tackle today's high risks of hacking, data manipulation, and data compromise.
- **Asset Management:** The ownership of digital assets is managed, and asset transfers are facilitated.
- **Smart Contracts:** A smart contract is a component of a blockchain-based system that can automatically enforce stakeholder-agreed rules and process steps. Once launched, smart contracts are fully autonomous; when contract conditions are met, prespecified and agreed actions occur automatically. These smart contracts can accelerate processes, allowing for fast and secure payments in digital assets, automated leasing, financing, maintenance, and other procedures. For example, in the context of last-mile delivery, once payment is received, the delivery of the product is automatically triggered, or once the freight is received, payment is automatically triggered.

Table 3-1 shows different types of blockchain technologies and gives some examples of applications in the smart mobility domain. Blockchain can be classified based on the governance models into public permissionless (e.g., Bitcoin, Ethereum, and IOTA), public permissioned (e.g., Sovrin and IPDB), private permissionless (e.g., Hyperledger Sawtooth in a permissionless mode), and private permissioned (e.g., Hyperledger Fabric, Hyperledger Sawtooth, Hyperledger Iroha, R3 Corda, and CULedger).

Blockchain is another component of digitizing society. This technology has the potential to reshape transportation and logistics systems enabling services such as authentication, access control, secure and fast payment (decentralized mechanism without central agency), seamless information sharing (e.g., empowering users by providing relevant information about mobility services), track (i.e., monitoring the process), and trace (i.e., uncover the origin). Imagine a person boarding a mobility platform like a bus empowered by blockchain and IoT technologies. Once the person boards the bus, the crypto-spatial layer notes the point of embarkation and the point of disembarkation and automatically charges the fare from the spatial wallet of the traveler and credits it to the spatial wallet of the transport utility company (Dasgupta, 2017).

Blockchain will increase the cost effectiveness of digital twins of smart mobility platforms and systems. Digital twins can be stored on a blockchain-based system for monitoring, diagnostics, and prognostics to guarantee the healthy, efficient, and sustainable operation of the platform, optimizing the operation and maintenance, discovering inequality of the design and in fleet management. This digital twin is a high-fidelity cloud-based virtual representation or a digital replica of the mobility platform that contains an up-to-date and accurate copy of the platform's properties and states throughout the entire life cycle of the platform. This life cycle spans from design to manufacturing to operation, feedback, and updates until the physical platform's end-of-life. For example, this digital twin powered by blockchain technology can be a single source of truth for each vehicle's maintenance data in order to eliminate illegal odometer manipulation.

Warning Odometer fraud (a.k.a. busting miles or clocking or odometer tampering or rollback) is the disconnection, resetting, or alteration of a vehicle's odometer manually or digitally with the intent to change the number of miles indicated.

The National Highway Traffic Safety Administration (NHTSA) estimates that more than 450,000 vehicles are sold each year with false odometer readings. This crime costs American car buyers more than $1 billion annually and puts safety at risk. In Canada, more than 89,000 vehicles are reported every year, with odometers that have been tampered with. A CarProof or Carfax report, which covers vehicles across Canada, may or may not have the odometer reading. In the United Kingdom, one in every 14 cars has a "mileage discrepancy." In Germany, it is estimated that every third car has been subject to illegal odometer manipulation. The fraudulent increase in value per car is estimated to be US $3,700 alone, which in Germany means almost $7.5 billion in fraud every year. To solve this problem, a blockchain-based system with an in-car connector can be used to regularly record the distances traveled by each vehicle, which acts as an ongoing, tamper-evident record of odometer readings (Heutger et al., 2018).

Table 3-1. Blockchain Types and Application Examples in Smart Mobility

Property	Public Blockchain	Consortium or Federated Blockchain	Private Blockchain
Access	Anyone	Single organization	Multiple selected organizations
Permission	Permissionless	Permissioned	Permissioned
Participants known?	Anonymous/ pseudonymous	Known identities	Known identities
Security	Consensus mechanism: Proof of work/ proof of stake	• Preapproved participants • Voting/multipart consensus	• Preapproved participants • Voting/multipart consensus
Transaction speed	Slow	Fast	Fast
Examples of applications in smart mobility	Mobile crowdsensing	• Blockchain-powered public transit operated by a city transit commission • Fleet management system of an organization	• Driving/testing data sharing • Vehicle digital twins among car OEMs (original equipment manufacturers) (Bosch and TÜV Rheinland) • Supply chain management • Usage-based insurance • Car/ride share transactions • P2P vehicle sharing services • Fast, elastic, and transparent last-mile delivery services (Ferrag and Maglaras, 2019)

Blockchain technology has also the ability to be a catalyst for peer-to-peer (P2P) mobility platform sharing systems. In these systems, a mobility platform can be a car (e.g., Drive Drive Car[3]), bike (e.g., Spinlister[4]), scooter, Personal Intelligent City Accessible Vehicle (PICAV), VTOL, SeaBubble, or any other personal transporter. Blockchain technology enables automating processes such as identification, payment, and asset transfer with smart contracts and

[3] https://drivedrivecar.com/
[4] www.spinlister.com/

smart keys, provides transparency, ensures traceability, and guarantees security as transactions are encrypted and immutable—once written.

Non-Fungible Tokens (NFT) is a trendy blockchain technology that is currently attracting the attention of the original equipment manufacturers (OEMs) and mobility service providers. According to a new report by NonFungible.com, the NFT market value tripled in 2020, reaching more than $250 million. NFTs are cryptographic assets with unique blockchain-based digital signature and can be used as a medium for commercial transactions to commodify digital assets in art, music, sports, and other popular entertainment.In smart mobility domain, NFT can be used to facilitate digital ownership through designating shared ownership of a vehicle and showing what percentage is owned by each party. West Coast Customs launches "CarCoin" NFT that will be available through a tiered membership program called "The CarCoin Fast Lane". Future plans include auctions of actual vehicles from classic episodes of "Inside West Coast Customs". NFT can be also used by mobility service providers to reward drivers and passengers with digital assets and loyalty points.

The decentralized security blockchain-based technology approach is considered promising in tackling security and privacy concerns of connected and automated vehicles. For example, the authors of (Rathee et al., 2019) emphasize blockchain technology as one of the best technologies in terms of confidentiality and security to control systems in real-time based environments. Dorri et al. (Dorri et al., 2017) design a decentralized Light Scalable Blockchain (LSB) architecture that can provide a secure overlay network between vehicles, OEMs, and service providers, where users' privacy is protected using a changeable public key. The authors state different applications including insurance and car sharing services to validate their proposed architecture. However, other researchers raise the issue of blockchain vulnerability to quantum attacks as quantum computers will be capable of breaking the vital cryptographic scheme.

The Mobility Open Blockchain Initiative (MOBI) was formed by GM, BMW, Renault, Ford, IBM, Hyperledger, IOTA, and ConsenSys (Ethereum) to focus on promoting standards and accelerating the adoption of blockchain, distributed ledger, and related technologies in smart mobility systems.

3.5. Internet of Things (IoT)

Internet of Things (IoT) (Atzori et al., 2010) is the technology that enables connecting any device to the Internet and/or devices to each other for sharing data and/or operation control. A much broader concept is the Internet of Everything (IoE). According to Cisco, IoE is about *"bringing together people, process, data, and things to make networked connections more intelligent and valuable than ever before, turning data into actions that create new capabilities,* *richer experiences, and unprecedented economic opportunity for businesses, individuals, and countries"* (Evans, 2012). The value of IoT/IoE is not in making one device or system smart but in enabling seamless processes across systems.

Generally speaking, in the context of smart mobility, a thing can be a driver, a passenger, a commuter, a transit operator, a pedestrian, or a cyclist with connected devices, a connected mobility platform, a connected seat, a connected tire pressure sensor, a connected traffic signal, a connected traffic sensor, a connected infrastructure, a connected reservation and booking system, or any other natural or manmade object that can be assigned an Internet Protocol (IP) address and is able to transfer data over a network.

Note According to Allied Market Research, the global IoT in transportation market is expected to reach $328.76 billion by 2023, growing at an estimated CAGR of 13.7% from 2017 to 2023.

IoT is a key foundational technology for connected infrastructure, connected vehicles, and connected customers/connected travelers. IoT applications in smart mobility include condition monitoring, predictive maintenance or remote diagnostics and prognostics, vehicle tracking, geo-fencing, traffic management and congestion control systems, fleet management, reservation and booking systems, and security and surveillance as shown in Figure 3-4.

For example, mobility platforms must keep running to guarantee the continuity of the service. Individual critical components such as propulsion, transmission, or steering systems play a crucial role in making this happen. Understanding the health of these critical equipment is sometimes overlooked with many kept running until they fail. Taking a brushless DC or an induction motor in a fully electric vehicle as an example, a motor failure can cause entire vehicle malfunctioning resulting in fatal accidents. Fortunately, electromechanical equipment like motors do not break without warning. Months before the faults occur, minimum vibration can be found. Weeks before the fault, apparent noise begins to develop. Days before the machine heats up and minutes before the breakdown, it starts to smoke. With motor condition monitoring, one can identify the slightest vibrations months in advance. In this case, failure can be prevented by replacing the bearing, for instance.

There are three major types of maintenance operations:

- **Improvement Maintenance:** Aims at reducing or eliminating the need for maintenance through modification, retrofitting, redesigning, or changing order in the mobility platform.

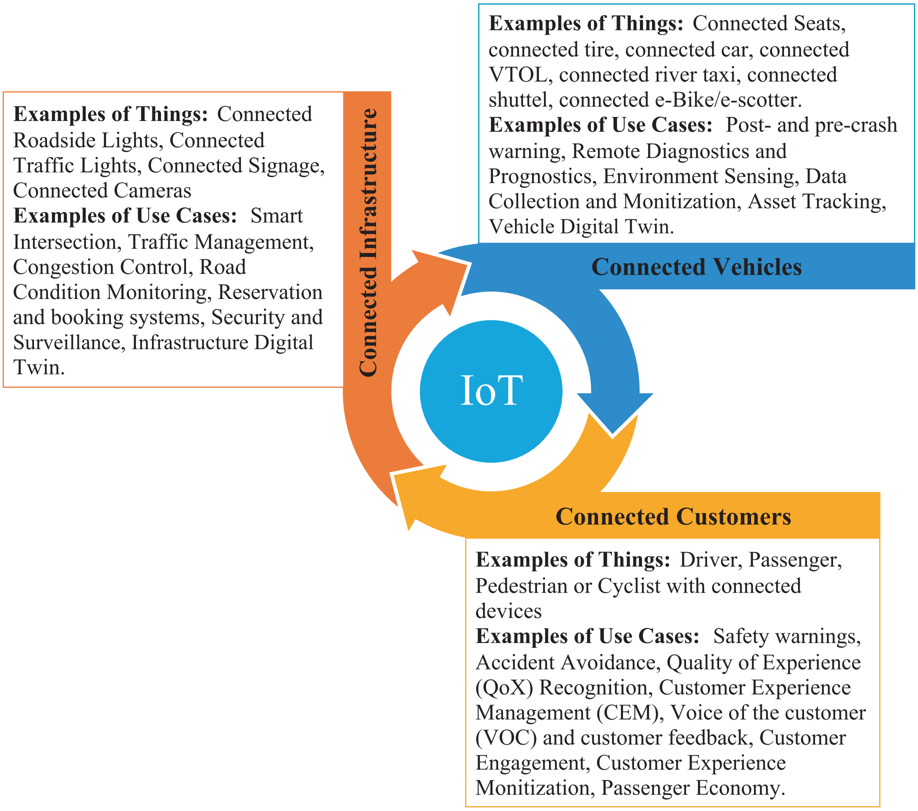

Figure 3-4. Examples of IoT Applications in Smart Mobility

- **Corrective Maintenance:** Is mainly event-driven and can be seen as an analogy to a human hand that intervenes in case of breakdowns, emergency, remediation, repairs, or rebuilds.
- **Preventive Maintenance:** Aims at preventing unscheduled downtime and premature equipment damage that would result in corrective or repair. This type of maintenance can be classified into reactive or equipment-driven, time-driven, and predictive maintenance. Reactive or equipment-driven is done when needed. In time-driven maintenance, preventive tasks are scheduled periodically or in a fixed interval or following hard time limits or using specific time. Predictive maintenance relies on condition monitoring of the equipment. Data is collected about the health of the equipment using IoT-connected sensors.

> The collected data is then analyzed in order to get insights into the possible failures and the causes of failures and recommend the preventive actions that help avoid future failures.

The dominant reason for inefficiency of the current predictive maintenance systems is the lack of factual data and real-time data analytics modules. This prevents the system from anticipating incipient problems and quantifying the actual need for repair or maintenance. According to a study published by ABB, the use of smart monitoring using connected sensors and data analytics can reduce the downtime of low-voltage motors by up to 70%, extend their lifespan by up to 30%, and cut energy consumption by as much as 10%.

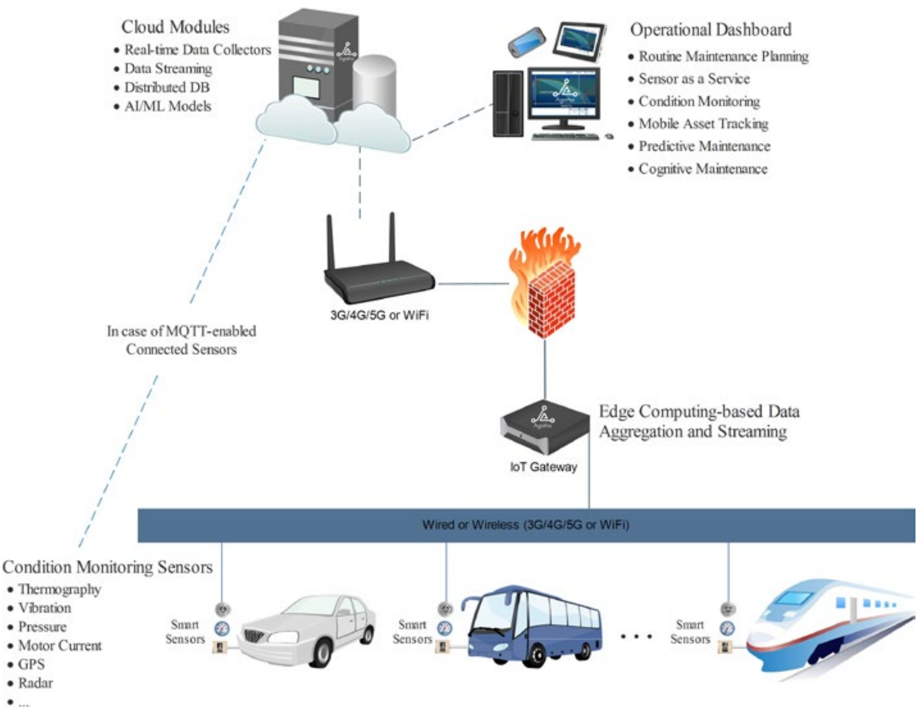

Figure 3-5. Cognitive IoT-Based System for Condition Monitoring, Asset Tracking, and Predictive Maintenance (Khamis, 2020)

Figure 3-5 shows a cognitive IoT-based predictive maintenance system invented by me (Khamis, 2020). This system facilitates the decentralized maintenance planning, remote monitoring of distributed stationary or mobile assets, prediction of possible failures, and recommendation of proactive actions to mitigate these risks in order to keep the continuity of the service. This system encompasses spatially distributed interoperable and accessible smart sensors able to selectively collect and share data about machine condition. The selectively collected data is then analyzed in order to get real-time insights and performance data, determine and dynamically update the likelihood of failures, and make timely decisions or recommendations.

3.6. Artificial Intelligence (AI)

AI successfully delivered many commercial products and services that touch everybody's life every day. AI aims at mimicking/reverse-engineering and augmenting biological intelligence to build intelligent systems/processes able to function and interact autonomously within structured/unstructured, static/dynamic, and fully/partially observable environments. This usually involves borrowing characteristics from human intelligence such as situation awareness, decision-making, problem solving, learning from the environment, and adapting to its changes (Khamis, 2019a). AI encompasses many subfields such as perception (e.g., object recognition, image understanding, speech recognition, speech synthesis, natural language understanding), knowledge representation, cognitive reasoning, machine learning, data analytics (e.g., descriptive, predictive, diagnostic, and prescriptive analytics), problem solving (e.g., constraint satisfaction, problem solving using search and optimization), distributed AI, and acting (e.g., virtual assistants and robots).

3.6.1. Evolution of AI

AI is an evolving technology, not a totally new one, as its seeds can be traced back to the classical philosophers and their efforts in modeling human thinking as a system of symbols that led to "connectionism" as a process of thinking. One should differentiate between two AI approaches, namely, top-down approach (white box or generative approach) and bottom-up approach (black box, discriminative, or data-driven approach). Traditional AI techniques follow the top-down deductive reasoning approach where they start out by formulating abstract and wide-ranging hypotheses about the world from preexisting knowledge and few examples. They make predictions about what the data should look like if those hypotheses are correct and then revise their hypotheses, depending on the outcome of those predictions (Gopnik, 2017) and upon receiving more observations. In contrast, modern AI techniques or computational intelligence techniques are characterized as bottom-up inductive reasoning (working on numeric data to infer symbols) and try to extract patterns from raw data (thousands or millions of examples). These modern AI techniques have powered different products and services through endowing them with the ability to discover and recognize complex patterns and trends (class, cluster, or anomalies) in archived, streaming, or live data and predicting future values and learning from examples and from observations at different levels of abstractions.

Understanding the limitations of current AI algorithms helps in deciding what problems can be solved by AI and how to improve the current algorithms or create new algorithms to cope with a wider range of real-world ill-structured problems (ISPs). As AI algorithms are used to endow the artificial systems or processes with intelligent behaviors, we should understand what is meant by an intelligent behavior. The behavior is what an external observer sees an artificial system/process doing. Broadly speaking, AI algorithms can be classified into individual or *i*-level algorithms and group or *g*-level algorithms. Both *i*-level algorithms and *g*-level algorithms can be used to implement low-level behaviors and high-level behaviors for an individual system/process ("agent" henceforth) and/or for a group of agents.

Low-level behaviors for individual agents may include context-aware data collection, object detection, obstacle avoidance, speech recognition, and object manipulation or acting upon the environment using the available effectors. Examples of low-level behaviors for the group include cooperative context-aware data gathering, information exchange, and cooperative manipulation. For example, context-aware data collection is the process of collecting data selectively and cognitively based on a certain context by a single agent or multiple agents in the case of cooperative data collection. Context is any information that can be used to characterize the situation. More details about context-aware systems are provided in the next chapter.

High-level behaviors for individual agents include interpreting the collected data, comprehending the situation, projecting the future consequences, and learning from experience. At the group level, high-level behaviors may include shared situation awareness, consensus finding, cooperative decision-making, group formation, communication relaying, and multiagent learning to name just a few. For instance, in cooperative learning, the sum of all agents' discounted future rewards (social welfare) has to be maximized, or a more amenable (for convergence) equilibrium or consensus such as the Nash equilibrium point has to be chosen (Vidal, 2006). *g*-level algorithms for high-level behaviors are more challenging to design compared to *i*-level algorithms for low-/high-level behaviors. This is mainly due to the fact that we do not fully understand how high-level behaviors in biological systems work. For example, human beings and all living organisms have the ability to gain information from the environment, as well as interpreting this information to take appropriate decisions. This ability requires performing different low-level and high-level functions. Low-level functions of the human brain such as seeing, hearing, smelling, tasting, and touching are fully understood and localized in the cerebral cortex. However, higher-level cognitive processes like information fusion, situation awareness, reasoning, decision-making, and learning are not fully understood. In general, we are only beginning to understand where these higher-level cognition functions occur in the brain, let alone how they are achieved (Anderson, 2005). Understanding how the brain works is arguably one of the greatest scientific challenges of our time (Alivisatos et al., 2012).

In human beings, cognition is achieved by patterns of neural activation in large sets of neurons. Analogously, multiagent systems must be able to perform different low-level and high-level behaviors. Let's consider picture compilation and learning as examples for individual low-level and high-level behaviors, respectively, in a human being. Building a complete picture of the environment could be achieved using a single sense or by the fusion of the data gathered from multiple senses. The human brain acts as a powerful fusion node. It fuses different information every time the senses are stimulated by appropriate signals. Our brain is continuously and perfectly fusing sight, hearing, smell, taste, and tactile information provided by our sensors, which are the eyes, ears, nose, tongue, and skin. This information is represented in terms of continuously varying electrochemical activities of neurons.

In the case of a high-level function like learning, we do not fully understand how the brain can learn from very few examples or sometimes from a single example, how it can generalize based on the previous experience, and how it can extract new concepts and show different signs of creative reasoning. For example, in an unknown environment, we used to wander around to explore and build a map about this environment. We can use this map later to navigate in this environment even if the lights are off or our eyes are closed. Where do we store this map and how do we learn to use it? New hybrid machine learning algorithms combining both top-down deductive reasoning and bottom-up inductive reasoning need to be developed to mimic human learning as a high-level function.

The previously discussed *i*-level picture compilation and learning behaviors are much more challenging to mimic at the *g*-level. We do not fully understand how to design *i*-level behaviors for a given desired *g*-level behavior given the fact that collective behavior is not simply the sum of each participant's behavior, as others emerge at the society level (Pasteels and Deneubourg, 1987). Understanding how the human brain perfectly performs both low-level and high-level cognitive functions in real time can help in designing efficient and adaptive algorithms for artificial systems/processes.

The several limitations of current AI algorithms to create low-level and high-level behaviors at the individual and group levels of the artificial agents make the current wave of AI a form of weak/narrow AI that functions in very narrow and well-defined domains. Strong/general/deep AI and superintelligence are yet to come. A machine equipped with superintelligence will be able to behave cognitively like a superhuman. Table 3-2 highlights the main difference between narrow AI, artificial general intelligence, and superintelligence.

The current media exaggeration and the noise about AI created a stereotyped view of strong AI in the society, while what we actually have now is a form of weak AI. This results in widening the gap between expectations and realities and makes people dissatisfied and less tolerant about the failure of AI tools. In reality, even the world's leading AI experts disagree on when superintelligence may happen. Some see it feasible by year 2045, and others guess hundreds of years or more. In order to mitigate this risk, the limitations of the current algorithms should be highlighted, and new algorithms should be developed to start the next wave of strong/general AI.

Table 3-2. AI Waves

Wave	Domain	Adaptation	Brainpower
Artificial narrow intelligence (ANI)	Domain-specific (image recognition, speech recognition, text mining, etc.)	No	Looks similar but not at the same level (suppresses brainpower of mouse)
Artificial general intelligence (AGI)	Cross-domain capability at *i*-level	Yes	Suppresses brain power of human
Artificial superintelligence (ASI)	Cross-domain capability at both *i*-level and *g*-level	Yes	Suppresses brain power equivalent to all human brains combined

The Defense Advanced Research Projects Agency (DARPA) has a very interesting vision for the AI waves (Figure 3-6). In their perspective, the first wave of AI was focusing on handcrafted knowledge or rule-based systems capable of narrowly defined reasoning tasks with very limited ability to perform perception task and no ability of learning or new concept generation or abstraction.

The second wave is the current wave of statistical machine learning–based systems able to recognize complex patterns and learn from large amounts of multidimensional data. Although these systems have high perception and learning capabilities, they still suffer from limited ability of abstracting, reasoning, causality analysis, explainability, and adapting to changing conditions in nonstationary environments. The third wave of AI is introduced to handle this limitation focusing on contextual adaptation, explainability, and commonsense reasoning to make it possible for machines to adapt to changing situations. In a highly regulated industry like mobility, aspects like reasoning, causality, explainability, and ability to handle drifts are very important especially when it comes to safety-critical features in mobility vehicles. According to DARPA, the third wave of AI known as "contextual AI" will handle the the limitations of the current wave of AI. Contextual AI is technology that is embedded in and understands human context and is capable of interacting with humans (Brdiczka, 2019). Focusing on contextual AI, DARPA announced in September 2018 a multiyear investment of more than $2 billion in new and existing programs called the “AI Next” Campaign.[5]

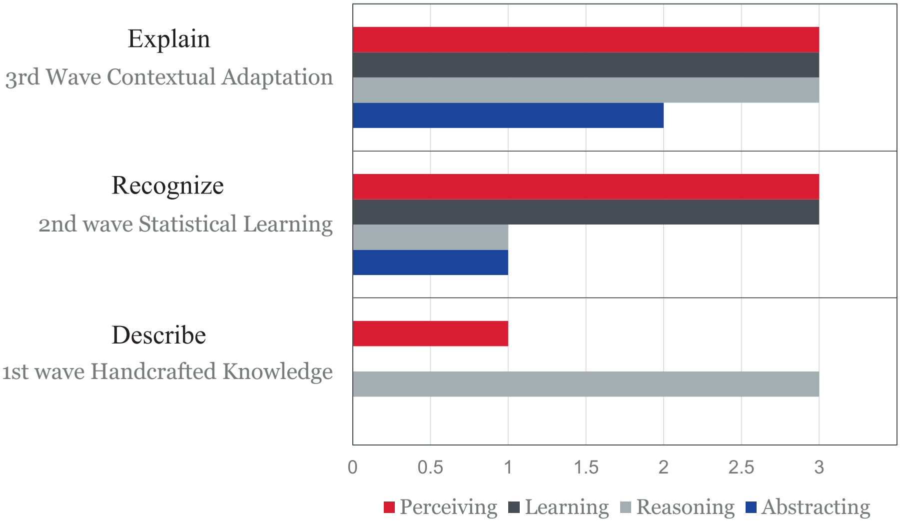

Figure 3-6. DARPA’s Vision for AI Waves

3.6.2. Statistical Machine Learning

Learning is to form an internal model of the external world (Dehaene, 2020). Machine learning (ML) is a subfield of AI that endows an artificial system/process with the ability to learn from experience and from observation without being explicitly programmed as illustrated in Figure 3-7.

Mitchell (Mitchell, 1997) defines ML as follows: *“A computer program is said to learn from experience E with respect to some class of tasks T and performance measure P, if its performance at tasks in T, as measured by P, improves with experience E.”* More comprehensively, Dehaene introduced seven key definitions of learning that lie at the heart of present-day machine learning algorithms. These definitions include learning is adjusting the parameters of a mental model, learning is exploring a combinatorial explosion, learning is minimizing errors, learning is exploring the space of possibilities, learning is optimizing a reward function, learning is restricting search space, and learning is projecting a priori hypotheses (Dehaene, 2020). In his book *The Master*

[5] www.darpa.mil/work-with-us/ai-next-campaign

Algorithm (Domingos, 2015), Professor Pedro Domingos summarizes the machine learning schools of thoughts into five main schools as illustrated in Figure 3-8.

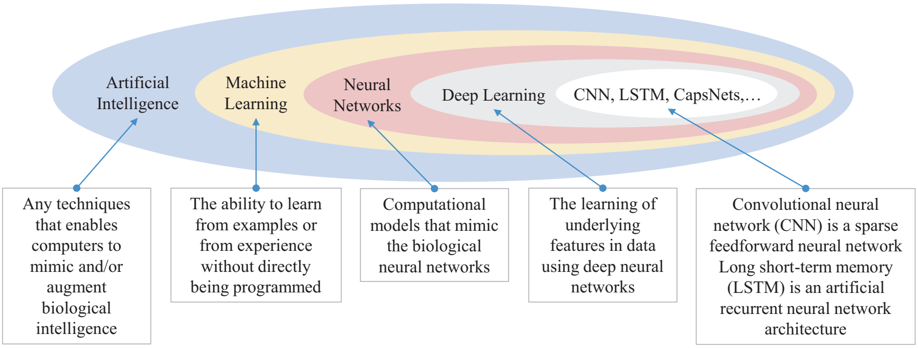

Figure 3-7. AI, ML, and Deep Learning

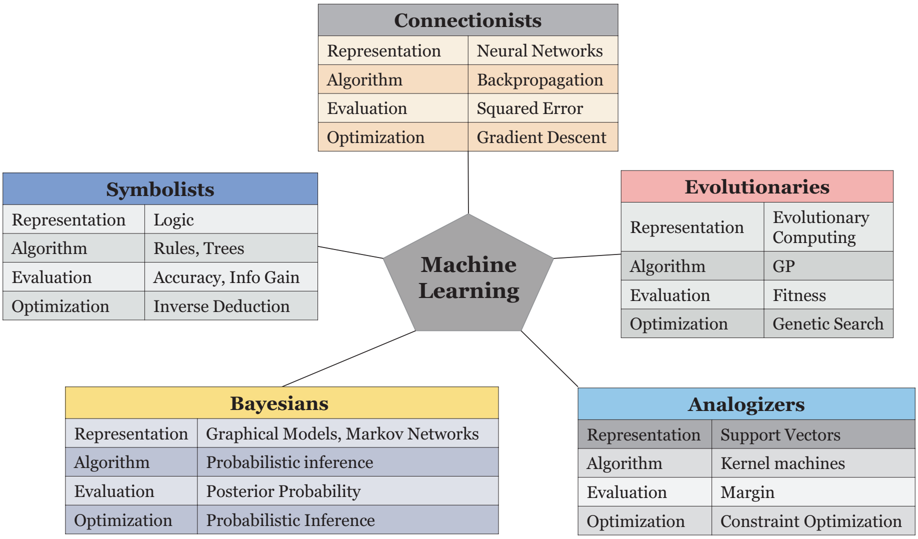

Figure 3-8. Machine Learning Approaches as per The Master Algorithm (Domingos, 2015)

- Bayesians with probabilistic inference as the master algorithm
- Symbolists with rules and trees as the main core algorithm within this paradigm
- Connectionists who use neural networks with backpropagation as a master algorithm

- Revolutionaries who rely on the evolution computing paradigm
- Analogizers who use mathematical techniques like support vector machines with different kernels

Nowadays, connectionist learning approaches have attracted most of the attention, thanks to their perception and learning capabilities in several challenging domains. These statistical machine learning algorithms follow a bottom-up inductive reasoning paradigm to discover patterns from vast amounts of data. They are based on the experimental findings that simple models trained on ultra-large datasets trump sophisticated models trained with less data (Halevy et al., 2009). Statistical machine learning is an inductive reasoning process (i.e., inferring general rules from a set of examples) that finds rules that are generally correct for most samples of the dataset of concern (Goodfellow et al., 2016). Statistical machine learning is currently the most famous form of AI due to its strong and increasingly diversified commercial revenue stream in different domains such as automotive, precision agriculture/smart farming, cognitive healthcare, EdTech, FinTech, and consumer electronics. Machine learning took off mainly due to the availability of the data, processing power (e.g., AI accelerators), open source tools, and R&D funding from public and private sectors. We are generating truly mind-boggling amounts of data on a daily basis. For example, there were 50 billion connected devices in 2020, assisted and automated driving vehicles generate 4–20 TB of data per day based on the level of driving automation, 350 million photos are uploaded to Facebook every day, Twitter generates 12 TB of data per day, 300 hours of YouTube videos are uploaded every minute, and Walmart collected 2.5 TB of customer data hourly. We are also witnessing huge investments from public and private sectors that lead to new efficient ML techniques and open source tools. For instance, China invests $7 billion through 2030, the European Union invested $24 billion between 2018 and 2020, France invests $1.8 billion in AI research until 2022, and SoftBank invests $108 billion in AI companies. According to CSET analysis of Crunchbase and Refinitiv data, US-based AI companies attracted about $25.2 billion in disclosed investment in 2019.

Machine learning algorithms are traditionally categorized into supervised, unsupervised, and reinforcement learning algorithms. First, supervised learning uses inductive inference to approximate mapping functions between data and labels/classes. This mapping is learned using already labeled training data. Classification (predicting discrete or categorical values) and regression (predicting continuous values) are common tasks in supervised learning. Second, unsupervised learning deals with unlabeled data through techniques like clustering and data association. In clustering, for example, n objects (each could be a vector of d features) are given, and the task is to group them based on certain similarity measures into c groups (clusters) in such a way that all objects in a single group have a "natural" relation to one another and objects not in the same group are somehow different. The third category of ML algorithms is reinforcement learning (RL), which is a weakly supervised learning technique that learns from interactions through a feedback loop or by trial and error. RL learns what to do (i.e., how to map a situation to actions) to maximize a numerical reward function. Deep reinforcement learning is used by DeepMind to develop a model able to learn how to play Atari video games better and faster than human skilled players without any human guidance (Mnih et al., 2015) and recently to explore and demystify the mysteries of Go accumulated in 3000 years in only 40 days. While DeepMind AlphaGo imitated human strategies and applied Monte Carlo tree search using three convolutional policy networks in a supervised manner, AlphaGo Zero does not imitate humans and did not see a single game and developed strategies that are not known for humans, thanks to reinforcement learning. In the context of assisted or automated driving vehicles or self-driving cars, supervised learning can be used for pedestrian detection, traffic light recognition, lane detection, voice biometrics, driver distraction recognition, and so on. Unsupervised learning can be used for crowdsensing and prognostic and predictive maintenance, while reinforcement learning is used to learn driver preferences and how to navigate through unknown dynamic environments.

As illustrated in Figure 3-7, deep learning (DL) is a subfield of machine learning concerned with learning of underlying features in data using deep neural networks enabling artificial systems to build complex concepts out of simpler concepts. Examples of deep learning include, but are not limited to, Stacked Denoising Autoencoders (SdA), Deep Belief Networks (DBN), Feedforward Neural Networks, Convolutional Neural Networks (CNN), Long Short-Term Memory (LSTM), Generative Adversarial Networks (GAN), and Capsule Networks (CapsNet). There are three main requirements to apply statistical machine learning or a data-driven approach, namely, there is existence of a pattern between the independent variables or features and the dependent variables, this pattern cannot pin out mathematically or analytically using attainable and mathematically tractable models, and last but not least there is availability of a comprehensive dataset. Even if these three requirements are met, there are still several problems to develop and deploy reliable and generic ML models. These challenges include the following:

- **Problem Characterization:** The first step in creating successful data-driven models is to understand the problem at hand, characterize it, and elicit all the required knowledge from a domain expert to help in collecting the relevant data and understanding the target requirements. The importance and the business value of the problem and its challenging aspects need to be understood. Different relevant independent variables and dependent variables need to be clearly identified by the domain expert. Independent variables include signals, control factors, and noise factors, while dependent variables represent the model response (Khamis, 2019b). Signals are stimuli required for fulfilling the model functionality. Edge/corner cases and adversarial cases should be also identified.

- **Data Collection:** There is no magic formula to give the required volume of data. However, it is important to collect comprehensive unbiased data considering different control factors, noise factors, edge cases, and adversarial cases.
- **Data Preprocessing:** Data should be preprocessed to deal with different imperfection aspects and to extract features with high discrimination power.
- **Modeling:** There is no universally superior ML algorithm according to the no free lunch theorem for machine learning. Statistical machine learning algorithms work under different underlying assumptions like the data is separable or the data has a specific distribution or the data is balanced or there is no spatial and/or temporal dependency between the data and so on.
- **Optimization:** Most model parameters such as weights in neural networks can be directly estimated from the data. However, model hyperparameters such as the number of estimators in random forest or deep learning architecture cannot be easily tuned and are often specified by the practitioner or by using heuristics.
- **Evaluation:** Different quantitative and/or qualitative evaluation metrics should be used to prove the efficacy of the trained model and evaluate and mitigate its bias and variance. Sometimes the best trade-off should be considered to match with certain constraints related to computational resources, memory footprint, or power consumption.
- **Verification and Validation:** Model verification and validation is a serious legal mandate in a highly regulated industry like transportation and especially important in safety-critical features. Both performance and robustness should be verified and validated to measure the ability of the learning algorithm to handle changes in the underlying training dataset and to understand how the trained model behaves with inputs with and without perturbations.

- **Learning Over Time and Adaptation:** In real smart mobility applications, data continuously evolve over time and change from one setting to another. This violates the assumption that training and test data have identical distributions. The actual settings that cause the generation of non-stationary data are typically: (1) sample selection bias, which is a systematic flaw in the selection process of data used for model building, (2) adversarial behaviors that try to work around the existing learned models, (3) time-evolving data, which is characterized as changing concepts along the time and (4) cross-dataset tasks where the training and testing samples are taken from different domains. Endowing the model with the ability to learn over time and to get updated in order to handle the data mismatch between training and inference in nonstationary environments is still a challenging task for data-driven models deployed in vehicles. Even if we manage to develop ML models able to learn over time with domain adaptation capability, the mismatch between the software life cycle and hardware life cycle will remain a challenge. AI is doubling its compute every 3.5 months, while updating hardware is slower (18 months according to Moore's law), more expensive, and sometimes not possible especially in the case of mobility vehicles or telematics systems.
- **Model Predictability and Interpretability:** Model unpredictability and the lack of the ability to interpret the results of the model are common problems of black box, discriminative, or data-driven models. Some ML models are like people, unpredictable and sometimes uninterpretable. Models trained using human behavior–based data as independent variables are more likely unpredictable compared to those trained using independent variables that strictly follow physics laws. For example, the human intent recognition model is less predictable compared to a model that predicts the stress-stain curve of a material. Model unpredictability is a serious issue in safety-related applications. These applications favor deterministic models. Nonlinear and nonmonotonic models are the most difficult to interpret (Patrick Hall and Phan, 2017). Monotonicity means that the relationship between the independent variables and the machine-learned response only changes in one direction making the model highly interpretable compared to nonmonotonic models.

Among the aforementioned challenges, data collection is discussed here in more detail. As mentioned previously, there is no magic formula to give the required volume of data. This volume depends on many factors, such as the complexity of the problem and the complexity of the learning algorithm, and directly impacts the learnability and the performance of the algorithm. Different relevant signals, control factors, and noise factors should be incorporated. Batch, near-real-time, or real-time data may be collected depending on the type of data analytics. It is also highly recommendable to include adversarial data as noise factors in order to improve the robustness of the model. As no one has infinite resources and infinite time to collect fully comprehensive data, most relevant representative data should be collected. For example, Figure 3-9 illustrates the Parameter diagram or P-diagram of a vision-based distracted driver detection model. In this diagram, the signal is mainly the driver picture taken by a precalibrated camera in the car. Control factors are design parameters that are changeable only during the data collection process and must be kept constant once the model is deployed. Control factors may include camera pan, zoom, focus, sampling rate, color mode, and so on. Noise factors influence the design and can be controllable during the data collection process, but these are not controllable after deploying the model.

The noise factors can include, but not limited to, scale changes, orientation changes, lightning conditions (illumination, shadows, and reflectance), and so on. Response is the primary intended functional output of the model. In this example, the output is the likelihood of what the driver is doing (safe driving, texting—right, talking on the phone—right, texting—left, talking on the phone—left, operating the radio, drinking, reaching behind, hair and makeup, or talking to a passenger). Finally, error states represent failure modes or effects of failure as defined by the end user when using the predictive model. In this case, error states can be false alarms or false negatives. Adversarial use cases should be considered. These use cases are the cases that can easily fool the algorithm due to their similarity with target use cases. In the previous example shown in Figure 3-9, let us assume we have two control factors (camera zoom and sampling rate) with three levels each and three noise factors (scale changes, orientation changes, and lightning conditions) with six levels each. The number of data collection experiments based on fractional factorial design can be calculated using this formula, L_R^{k-p}, where L is the number of levels, k is the number of factors to be investigated, p designates the fraction of the experiment design (p=0 for full factorial, p=1 for half factorial, and p=2 for quarter factorial), and R is the resolution (Resolution I indicates one-way or no interaction between the factors, Resolution II for two-way interactions, Resolution III if there are one-way and two-way interactions cofounded, and Resolution V if there are one-way and four-way interaction or two-way and three-way interaction aliasing). In our example, assuming full factorial design and Resolution I, the number of experiments for all control and noise factors will be $3^2 \times 6^3 = 1,944$ runs. Assuming that each experiment takes 10 minutes, the total duration of the data collection will be 324 hours or 40.5 days assuming 8 hours per day. A subject matter expert should be able decide the importance of each factor and the practical levels to be considered as collecting a fully comprehensive dataset (full factorial dataset) is usually impossible due to time and resource constraints. A fractional factorial dataset with the key factors and frequently occurring levels can be used to build efficient models with acceptable levels of transferability and generalizability.

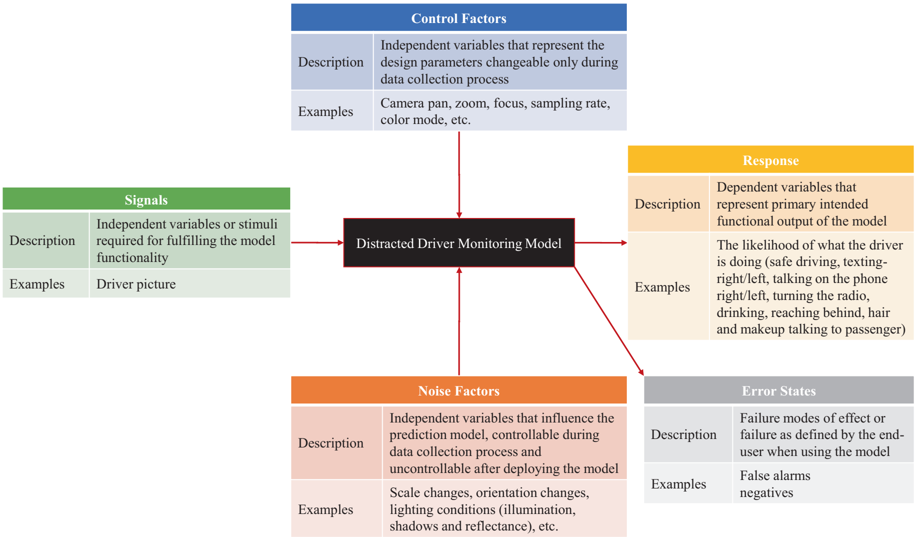

Figure 3-9. Visual Feature–Based Distracted Driver Monitoring Model

3.6.3. AI for Smart Mobility

AI is a foundational technology and a driving force behind several existing and emerging mobility systems and services we are currently witnessing. According to the Artificial Intelligence in Automotive survey conducted by Wards Intelligence in 2018, 40.6% of the participants think that advanced driver assistance systems (ADASs) will be the first vehicle systems to use AI, 32.5% infotainment/voice recognition, 17.6% diagnostics, and 9.2% vehicle-to-infrastructure (V2I)/vehicle-to-vehicle (V2V) communication.

Important In a survey conducted by the McKinsey Center for Future Mobility on 474 companies in the mobility and AI space, 38.2% of these companies focus on using AI for autonomous driving, 19.4% to improve in-vehicle experience, 16% in manufacturing and supply chain management, 9.3% in fleet management, 8.9% in quality assurance, 5% in traffic/infrastructure inspection, and 3.2% in predictive maintenance (Cornet et al., 2017).

AI is used along the entire life cycle of the mobility platform from design to manufacturing to operation to feedback and updates to disposal and recycling as illustrated in Figure 3-10.

Potential applications of AI and ML in smart mobility include, but are not limited to, the following:

- Creating incremental, disruptive, and transformational innovative features, services, or new business models to improve customer experience, gain competition, and/or serve low-end or unserved consumers.
- Automatic gathering of relevant data and generating several insights to draw a larger conclusion and make better decisions.
- Identifying the data that's available to the mobility company but is not being used and left in the dark (dark data).
- Developing different levels of situational awareness to enable the perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future. Examples include vehicle diagnostics and prognostics; vulnerable road user (VRU) detection, localization, and intent recognition; user behavior recognition (physical, visual, or physiological); user behavior learning and modeling (age recognition, gender recognition, preference recognition, etc.); and predictive infotainment.
- Enabling ADASs and automated driving tasks (perception, planning, control, learning, and adaptation) in changing environments.
- Supporting digital transformation (e.g., generative design, test automation, over-the-air (OTA), Robotic Process Automation (RPA), intelligent agent assistants, digital twin of the mobility platform, dispatch and routing optimization, fleet management, digital go-to-market (GTM) tools, etc.).

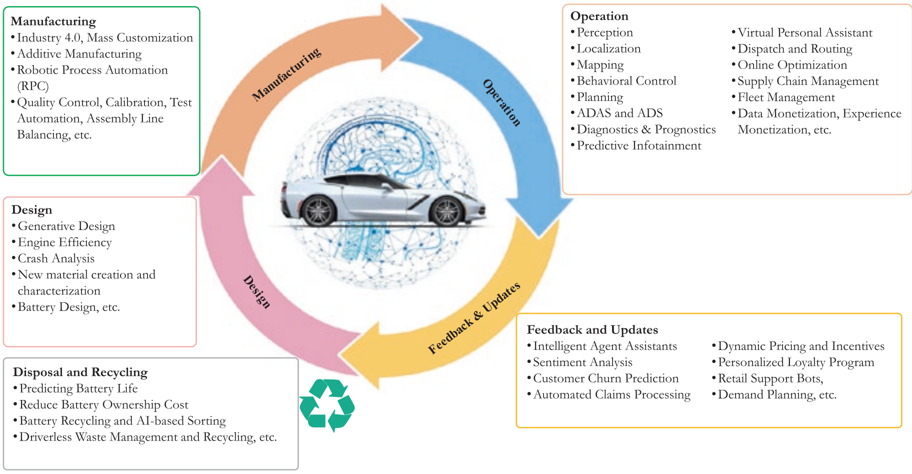

Figure 3-10. Examples of AI Applications in Vehicles

Moreover, AI search algorithms and modern metaheuristics optimization techniques have the ability to handle complex ill-structured people mobility problems, logistics problems, and infrastructure optimization problems. The following subsection describes these ill-structured problems and explains the potential of AI algorithms to solve them.

3.6.4. AI for Ill-Structured Problems in Smart Mobility

Real-world problems can be broadly classified into well-structured problems (WSPs) and ill-structured problems (ISPs). Figures 3-11 illustrates the main components of well-structured problems.

Herbert Simon in Simon (1973) described the six main characteristics of WSPs as follows:

1. There is a definite criterion for testing any proposed solution and a mechanizable process for applying the criterion.

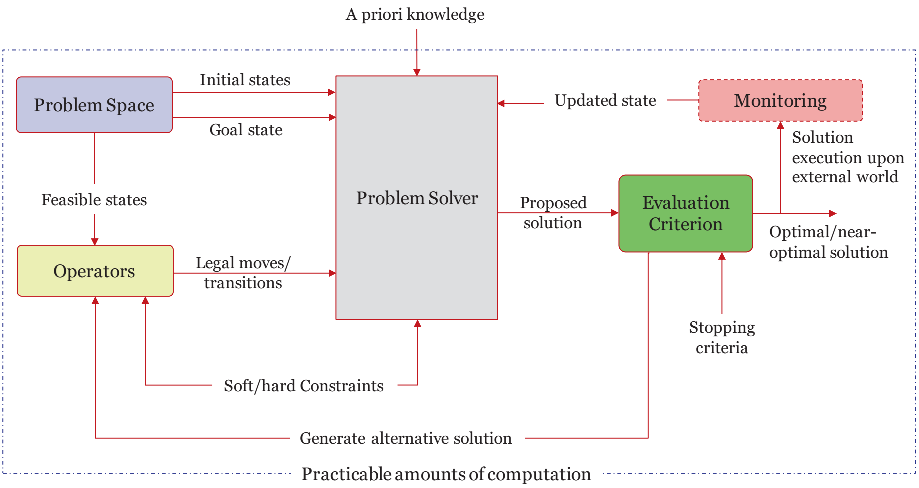

Figure 3-11. Well-Structured Problems (WSPs)

2. There is at least one problem space in which the initial problem state, the goal state, and all other states that may be reached, or considered, in the course of attempting a solution of the problem can be represented.

3. Attainable state changes (legal moves) can be represented in a problem space, as transitions from given states to the states directly attainable from them. But considerable moves, whether legal or not, can also be represented—that is, all transitions from one considerable state to another.

4. Any knowledge that the problem solver can acquire about the problem can be represented in one or more problem spaces.

5. If the actual problem involves acting upon the external world, then the definition of state changes and of the effects upon the state of applying any operator reflects with complete accuracy in one or more problem spaces the laws (laws of nature) that govern the external world.

6. All of these conditions hold in the strong sense that the basic processes postulated require only practicable amounts of computation and the information postulated is effectively available to the processes—that is, available with the help of only practicable amounts of search.

Ill-structured problems are complex discrete/continuous problems without algorithmic solutions/general problem solvers and can be characterized by one or more features such as lack of mathematical models, data imperfection, unclear goals, different views of the problem, conflicting solutions, stochastic actions, or context sensitivity. These features may lead to constraints and difficulty in defining the problem space, generating legal moves/transitions or alternative solutions, evaluating the proposed solution, or defining stopping criteria and updating the mechanism for the states. Taking data imperfection as an example, different data sources can be used in vehicle environments to provide information about the driving environment that includes the status of the driver, the vehicle, and the surrounding. These data sources could include a wide range of physical sensors, human-generated information and data retrieved from the Internet. Physical sensors include, but are not limited to, range finding sensors, cameras, vehicle speed sensors, tire-pressure monitoring sensors, etc. The data coming from these sensors used to be called "hard data" and is quantitative in nature. Humans can act as soft sensors providing dynamic observations about their status/preferences, the vehicle, and weather/road conditions. This information is called "soft data". Another source of soft data is the open source information on the Internet that can be retrieved and mined in order to provide more observation about the traffic for example. Next generation ADASs will rely on integrating and fusing multimodal data coming from the aforementioned sources. Handling soft data is more challenging than hard data due to their qualitative nature, subjectivity and inherent incompleteness. Both hard and soft data can suffer from different imperfection aspects. This data imperfection may result in wrong beliefs about driver/car/environment state. These wrong beliefs can lead consequently to wrong decisions and actions. Data imperfection can be classified into uncertainty, imprecision and granularity. Data is uncertain when the associated degree of belief or confidence degree about what is stated by the data, is less than 1. Imprecise data refers to several, rather than only one, object(s). Imprecision can take different forms such as vagueness, ambiguity and ignorance/incompleteness. Data granularity is another data imperfection aspect that refers to the ability to distinguish among objects, which are described by data, being dependent on the provided set of attributes. For example, uncertainty may be caused by several factors such as environments, sensors, vehicles, models, or computation. Physical worlds are inherently unpredictable. While the degree of uncertainty in well-structured environments such assembly lines is small, environments such as highways and urban canyons are dynamic and most of the time unpredictable. Sensors are also imperfect devices with errors. They are inherently limited in what they can perceive. Limitations arise from two primary factors, range and resolution of a sensor, which are subject to physical laws (Fox et al., 2005). For example, cameras cannot see through obstacles like other vehicles or walls, and even within the perceptual range, the spatial resolution of camera images is limited. Sensors are subject to noise, which perturbs sensor measurements in unpredictable ways and hence limits the information that can be extracted from sensor measurements (Choi and Lee, 2007). This noise causes random/nondeterministic errors that in contrast with systematic/deterministic errors are characterized by a lack of repeatability in the output of the sensor. Moreover, the uncertainty of the observations can arise from other factors such as false measurements, unreliability and deception of data sources, existence of multiple targets and cluttered observations, evasive actions of rapidly maneuvering targets, and unknown correlations (Mahler, 2007). Some actuators in vehicles may be inaccurate and to some extent unpredictable due to effects like control noise and wear and tear. Models are abstractions of the real world. As such, they only partially model the underlying physical processes of the vehicle and its environment (Fox et al., 2005). Moreover, approximated models are sometimes considered in order to guarantee real-time response.

Some problems such as clustering and the traveling salesman problem (TSP) may be well structured in principle, but they are ill-structured in practice due to impracticable amounts of computation required to solve these problems in real time. In TSP, given *n* cities, a traveling salesman must visit the *n* cities and return home, making a loop (round trip). He would like to travel in the most efficient way (fastest way, cheapest way or shortest distance or some other criterion). Search space in TSP is very big, for example, if the traveling salesman is to visit the 14 major cities in the Greater Toronto Area (GTA) as illustrated in Figure 3-12.

There are 13!= 6,227,020,800 possible tours in the case of asymmetric TSP. In asymmetric TSP, paths may not exist in both directions, or the distances might be different, forming a directed graph. Traffic collisions, one-way streets, and airfares for cities with different departure and arrival fees are examples of how this symmetry could break down. This is an NP-hard problem. TSP is used as a platform for the study of general methods that can be applied to a wide range of discrete optimization problems. These problems include, but are not limited to, the problem of arranging school bus routes to pick up the children in a school district, assignment of routes for planes of a specified fleet, transportation of farming equipment from one location to another to test soil, scheduling of service calls at cable firms, the delivery of meals to homebound persons, the scheduling of stacker cranes in warehouses, and the routing of trucks for parcel post-pickup and a host of others.

Figure 3-12. Traveling Salesman Problem (TSP) in the Greater Toronto Area (GTA)

In the context of smart mobility, ISPs can be categorized into people mobility problems, logistics problems, and infrastructure problems. Examples of people mobility problems include

- **Multi-criteria Optimal Routing**: To improve existing routing algorithms taking into consideration different criteria beside the shortest time such as number of left turns, number of intersections, avoiding passing by dangerous zones, capacity of the roads, tolling, and so on.
- **The Capacitated Vehicle Routing Problem**: Where a service provider has to serve a set of customers using a fleet of homogeneous vehicles based at a common depot. Each customer has a certain demand for goods, which initially are located at the depot. The task is to design vehicle routes starting and ending at the depot such that all customer demands are fulfilled.

- **Bus Scheduling Problem**: The objective of the scheduling is to obtain a bus loading pattern such that the number of routes is minimized, the total distance traveled by all buses is kept at minimum, no bus is overloaded, and the time required to traverse any route does not exceed a maximum allowed policy.
- **Emergency Dispatch and Routing**: For first-response emergency vehicles like ground/air ambulances, fire trucks, police cars, or search and rescue vehicles.
- **Peer-to-Peer (P2P) Vehicle Sharing Services, Demand-Responsive Transit (DRT), Dial-a-Ride or Paratransit, Microtransit, Ridesharing Services, Ridehailing or Ridesourcing Services, or Ridesplitting/Carpooling Services**: To maximize vehicle occupancy or expected profit during normal and surge times. During slow hours, drivers are willing to pick up a passenger who's far away. If it is super busy, drivers are less likely to accept trips with longer pickup times since they figure they will get a closer request if they wait a few more minutes. This knowledge can be used to generate plausible optimizations for the ride share apps.
- **On-Demand Responsive Transit During Pandemics**: To support the transportation of essential workers and essential trips to pharmacies and grocery stores for the general public especially the elderly taking into consideration store operating hours, capacity, and online delivery options.
- **Fitness Planner**: To create a fitness assistant for runners and cyclists that seamlessly automates the multiple tasks involved in planning fitness activities. The planner assesses an athlete's current fitness level and individual training goals in order to create a fitness plan. The planner also generates and recommends geographical routes that are both popular and customized to the user's goals, level, and scheduled time, thus reducing the challenges involved in the planning stage. The suggested fitness plans are continuously adapting based on each user's progress within their fitness goals, thus keeping the athlete challenged and motivated.
- **Trip Itinerary Planning**: Planning an itinerary for the day is perhaps the most challenging and time-consuming task when it comes to traveling. It is always ideal to maximize the user's time by visiting the best attractions available; however, choosing from a large pool of highly

rated sites significantly makes the decision-making process more difficult. This problem can be addressed by the development of a trip planner that minimizes total commute time, maximizes the average ratings of attractions contained in a solution, and maximizes the duration spent at each of these attractions and effectively minimizes idle time when someone visits a city.

- **Motion Planning for a Shared or Privately Owned AV or ZOV (Zero-Occupant Vehicle)**: This problem relates to how to find a collision-free path for a vehicle from a start position to a given goal position, amid a collection of obstacles. Path planning can be seen as an optimization problem, which aims at improving some system objectives with several constraints. System objectives may be the traveling distance, traveling time, and consumed energy. However, the traveling time is the most common objective.
- **Deadheading Problem**: Minimizing deadheading for first-/last-mile transportation companies (minimize the miles driven with no passenger).
- Other problems include, but are not limited to, optimal MaaS bundling, multimodal seamless trip planning, eco-routing in e-mobility, micromobility first-/last-mile routing, and communication relaying.

Logistics problems may include the following:

- **Last-Mile Delivery Scheduling and Rescheduling**: Finding the optimal schedule for delivery cargo-bikes, semi- and fully autonomous last-mile delivery trucks, self-driving delivery droids, delivery drones, e-Palette, postal delivery, driverless deliveries, and privately owned AV to maximize customer satisfaction and minimize delivery cost taking into consideration the capacity of the vehicle, type of delivery service (couple of days delivery, next-day delivery, or same-day delivery with some extra surcharge), delivery time, drop-off locations, and so on.
- **Multi-criteria Optimal Routing**: Conventional navigation apps like Google/Apple Maps or Waze caused a lot of problems because they are not taking into consideration several criteria and important hard and soft constraints to achieve optimal delivery vehicle routing during both liveheading and deadheading. Deadheading or dead mileage represents the idle distance

covered by the delivery vehicle without carrying any load. Liveheading represents the distance traveled while the delivery vehicle is loaded. Delivery vehicle routing can be optimized taking into consideration multiple criteria and constraints. Examples of objective functions to be optimized for both liveheading and deadheading problems using this optimization engine include fuel consumption, travel time, travel distance, number of traffic signals of a route, number of left turns, number of intersections, number of roundabouts, and number of bus stops of a route. Example of hard constraints include delivering within the time window given to the customer and not exceeding the capacity of the delivery vehicles. Soft constraints can be avoid passing by arterial roads, avoid passing by school zones during drop-off and pick-up times, avoid passing by streets with high elevation to save fuel, avoid passing by bridges during lift times, avoiding passing by dangerous zones, avoid passing by railway crossing, etc. Multiple conflicting objectives can be handled using a preference-based multi-objective optimization procedure or ideal multi-objective optimization procedure and the Pareto optimization approach. In the former approach, duality principle is applied first to transform all the conflicting objectives for maximization or minimization and then converts these multiple objectives into a single or overall objective by using a relative preference vector or a weighting scheme to scalarize the multiple objectives. However, finding this preference vector is highly subjective and not straightforward. The latter approach relies on finding multiple trade-off optimal solutions and chooses one using higher-level information. This procedure reduces the number of alternatives to an optimal set of nondominated solutions known as the Pareto Frontier, which can be used to make strategic decisions in a multi-objective space.

- Other problems include dynamic order orchestration, self-driving vehicle (SDV) coordination in warehouses, truck platooning, flocking, and delivery fleet management.

Examples of infrastructure problems are

- **Optimal Placement of Traffic Sensors**: The precise and continuous collection of traffic data enables road operators to monitor and manage traffic flows in real time at minimum costs. This information also helps city planners in smart transportation planning for more sustainable and efficient urban mobility. Traffic monitoring systems encompass a vast array of sensors that provide valuable information about road occupancy/headway/gap/congestion, vehicle counting and classification, counting of vulnerable road users (VRUs) such as pedestrians and cyclists, and so on. These sensors include, but are not limited to, inductive-loop detectors, cameras, radars, BLE and WiFi detectors, and so on. Sensor placement has an enormous impact on the performance of the traffic monitoring system. The sensor placement problem can be seen as a combinatorial problem that involves the placement of a set of *N* sensors with different fields of view in a set of *M* areas of interest.

- Other problems include optimal placement of city bike terminals; optimal placement of bus stops; optimal placement of walking routes and cycling lanes for active, soft, and inclusive mobility; optimal allocation of stacks and racks/pickup and drop-off points for mobility on demand systems; optimal placement of stations for micromobility; optimal placement of EV charging stations; smart parking (allocation, dynamic pricing, navigation); dynamic congestion charging and road pricing; traffic flow optimization; AV coordination and self-organization; planning/replanning of transport corridors and city streets to accommodate more pedestrians, cyclists, and riders in shared transportation and less cars; optimal drone deployment for EV charging; and optimal allocation of air taxi takeoff and landing locations.

AI search algorithms and modern metaheuristics optimization techniques can efficiently explore the search space in order to find (near-)optimal solutions for these complex problems in reasonable time. The benefits of applying metaheuristics in solving ill-structured problems in smart mobility systems are multifold. First, metaheuristics can find high-quality (i.e., near-optimal) solutions at a reasonable computational cost and are often seen as global optimizers. Second, metaheuristics approaches are often robust to problem size, problem instance, and random variables. Finally, compared to pure random search, metaheuristics algorithm randomness is not used blindly but in an intelligent, biased form. I show how AI and metaheuristics can be used to solve these problems in the course "Bio-inspired Algorithms for Smart Mobility" I developed and teach at the University of Toronto. This course provides a comprehensive introduction to AI search algorithms and highlights their power in solving complex discrete and continuous problems in the context of smart mobility. An open source GitHub organization of the course is available here: `https://github.com/SmartMobilityAlgorithms`. This organization contains several Python repos about deterministic and stochastic bio-inspired search algorithms and examples of potential use cases in smart mobility systems and services.

3.6.5. Keys to Successful AI/ML Adoption

The following five prerequisites or crucial elements should be considered for successful AI/ML technology adoption:

- **Unified Strategy:** Companies need to have a clear and unified strategy to leverage the full potential of the fast-evolving yet challenging AI and ML technologies and coordinate advanced research and development for a cross-functional innovation.
- **AI Governance Framework:** To address important aspects for responsible AI such as performance metrics, cybersecurity, privacy, ethics, bias, transparency, liability, legal and policy compliance, and trustworthiness.
- **Technical Protocols and Guidelines:** Such as data collection protocols, safety verification and validation regulations, and deployment, robustness, and OTA update procedures.
- **Infrastructure and Tools:** Companies also should provide adequate hardware infrastructure and software tools for data handling, model development, hyperparameter optimization, model acceleration and compression, and model deployment (cloud or edge deployment) and OTA updates.
- **AI Culture and Talent Development:** Last but literally not least, it is very important to spread the AI culture and develop the talents and keep educating them about recent advances in this fast-evolving field. We need to fully understand both the strengths and the limitations of the current wave of AI for not over-trusting the technology and creating false arguments especially in critical safety-related projects.

3.7. Robotics

Robotics is the engineering science and technology of robots that involve the design, manufacture, control, and programming of robots; the use of robots to solve problems; the study of the control processes, sensors, and algorithms used in humans, animals, and machines; and the application of these control processes and algorithms to the design of robots. Robotics is the intelligent connection of perception (thinking about sensing) to planning (thinking about actions) (Brady, 1985).

Robotics is a major foundational technology for smart mobility. Smart mobility platforms such as robo taxi or robotic chauffeur, aerial taxis, autonomous river taxis, automated people movers, delivery drones, self-driving shuttles, and exoskeleton used for walking assistance began to emerge from robotics research labs and are based on advances in robotics in terms of mechanical design, locomotion systems, perception, planning, control, navigation, and coordination algorithms. For example, automated driving vehicles are considered intelligent robotic systems that employ intelligent techniques to mimic human driver intelligence in perception, decision-making, problem solving, learning from the environment, and adapting to its changes. Like a mobile robot, a self-driving vehicle should be able to answer questions like "Where am I?", "Where am I going?", "What does the world look like?", "How to explore an unknown environment?", "How can I get there from here?", "How to achieve intelligent connection between perception and action?", "How to deal with unexpected events?", and "How to interact properly with other actors in the environment such as other vehicles and vulnerable road users (VRUs) like pedestrians and cyclists following formal and sometimes informal rules of interaction?"

Generally speaking, vehicles can be classified according to the level of autonomy into human-operated, semi-autonomous, and fully autonomous vehicles. Figure 3-13 illustrates these three levels and the relation with the control taxonomy proposed in Draper (1994) in terms of type of control, system role, human tasks, and critical information in each level.

Human-operated vehicles represent vehicles that must be operated by a human on-site or remotely. In semi-autonomous vehicles, the role of the system becomes bigger where the vehicle itself can control and monitor multiple tasks. An autonomous vehicle can function, decide, and interact autonomously within structured, unstructured, static, dynamic, and observable or partially observable environments without explicit human guidance (Bayat et al., 2016). Fully autonomous vehicles do not exist yet as these systems should have self-governing or self-x capabilities such as self-configuration and management, self-adaptation or adaptability, self-protection, self-diagnosis and self-healing and repair, self-optimization, self-synchronization, and self-organization. For instance, a fully autonomous system with self-healing and repair capability will be resilient and able to handle transient failures in dynamic environments. Hollnagel (Hollnagel, 2009) describes four central abilities that characterize resilient systems. These abilities include anticipating what may happen (what to expect, monitoring what is going on (what to look for), responding effectively when something happens (what to do), and learning from past experiences (knowing what has happened).

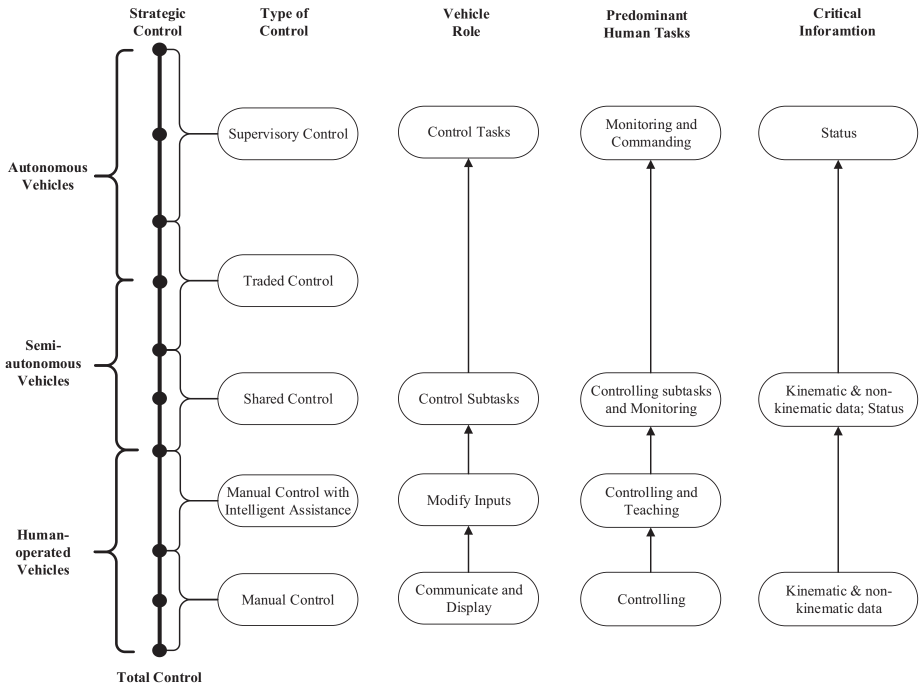

Figure 3-13. Levels of Autonomy

In Figure 3-13, the control level determines the relative importance and frequency of the tasks carried by the human. It refers to the nature of human responsibility for vehicle functioning, which ranges from total control to strategic control. During total control, the human is responsible for all decisions, from strategic planning to trajectory control. At the other end of this continuum, the human is only responsible for relatively long-term plans, at least while the vehicle is performing the task. As shown in Figure 3-13, the levels of control are

- **Manual Control:** At this level, the human operator entirely controls vehicle functions; the task of the vehicle is to display operational and contextual information and act on human inputs.
- **Manual Control with Intelligent Assistance:** As more vehicle intelligence becomes available, the human may be able to teach the vehicle rudimentary information about the work site, such as defining regions that should not be entered. The vehicle is able to modify information

displays and modify human inputs to provide guidance. As the vehicle becomes more capable, the human is able to shed more responsibility.

- **Shared Control:** At this level, the human is responsible for controlling some subtasks while the vehicle simultaneously controls others.
- **Traded Control:** The vehicle and human are consecutively responsible for subtasks, that is, sometimes the robot is in complete control and sometimes the human is in control.
- **Supervisory Control:** At this level, the vehicle is responsible for controlling all tasks and the human is monitoring it and occasionally intervenes in case of emergency. The human only enters the control loop when abnormal situations arise.

Similarly, the SAE (Society of Automotive Engineers) International (SAE On-Road Automated Vehicle Standards Committee and others, 2018) defines six levels of driving automation as explained in the next chapter.

NASA's Robotics, Tele-Robotics and Autonomous Systems road map working group made an interesting distinction between automated systems and autonomous systems (National Research Council, 2012). They define an automated system as

> *a system that follows a script, albeit a potentially quite sophisticated one; if it encounters an unplanned-for situation, it stops and waits for human help. The choices have either been made already, and encoded in some way, or will be made externally to the system. In contrast, an autonomous system is a system that resolves choices on its own. The goals which the system is trying to accomplish are provided by another entity; thus, the system is autonomous from the entity on whose behalf the goals are being achieved. The decision-making processes may in fact be simple, but the choices are made locally.*

Based on this definition, we can claim that vehicles that operate in SAE levels 1, 2, and 3 represent automated systems, while those in levels 4 and 5 represent systems with higher degree of autonomy but not fully autonomous due to the lack of self-governance capabilities previously explained.

Major global auto OEMs (original equipment manufacturers) have several frameworks to develop automated driving systems (ADSs) or self-driving vehicles. GM develops an ADS following a ground-up, seamless integration iterative approach (General Motors, 2018). Waymo's framework encompasses the following four steps (Hedlund and North, 2018):

- **Locate:** A detailed three-dimensional map of all roadways within its operational design domain (ODD) is provided to an ADS. The map includes road profiles, curbs and sidewalks, lane markers, crosswalks, traffic signals, speed limits, signage, fixed objects, and other relevant features.
- **Scan:** ADS sensors scan the roadway and surrounding areas in all directions for objects around the vehicle: other vehicles, bicyclists, pedestrians, animals, objects in the roadway, potholes, and temporary signage. They interpret any traffic controls including traffic light color or railroad crossing gates and signals. The scanners' range extends for hundreds of meters.
- **Predict:** The ADS predicts the trajectory of every movable object based on its current location and its previous movements and speed. The predictions take into account how other objects may be affected by roadway features or conditions, such as traffic signals or a vehicle in the travel lane. These predictions are updated many times each second.
- **Act:** The ADS then chooses its trajectory and any speed or steering adjustments needed for this trajectory.
- **Repeat:** Run the same four steps continually.

This framework is somehow similar to the Observe, Orient, Decide, and Act (OODA) loop commonly used in a combat operations process. During the "Observe" step, the vehicle tries to obtain a cohesive understanding of the world based on processing data from different multimodal sensors such as cameras, LiDAR, short-range and long-range radars, and so on. During the "Orient" step, a representation of the world is created to help the vehicle in comprehending the situation and in selecting a course of action, planning, and making decisions accordingly in the "Decide" phase. During the "Act" stage, the vehicle executes the planned actions, keeps monitoring the situation, and replans if necessary.

The cognitive cycle of Sense-Aware-Decide-Act-Adapt-Learn is a more comprehensive way to explain the capabilities of autonomous vehicles from the robotics perspective. This cycle extends the commonly known deliberative cycle of Sense-Decide-Act commonly used in robotics by adding situation awareness, adaptation, and learning capabilities as illustrated in Figure 3-14. In these systems, data is collected from different hard and soft data sources. Hard data is collected from physical sensors (e.g., cameras, radar, LiDAR), and soft data includes virtual sensing, fused data, human input, and social media data. The collected data is processed to achieve different levels of situation awareness such as the perception of elements in the environment within specific time and space constraints, the comprehension of their meaning, and the projection of their status in the near future and possible consequences (Endsley, 2016).

As illustrated in Figure 3-14, perception results in a compiled picture of the environment that may include several subprocesses such as object localization (or tracking), object recognition, and identification. Comprehension capability integrates this information to produce a more comprehensive picture of the world that shows the relations between the recognized objects. Projection capability projects the future actions of the objects in the environment. Generally speaking, the output of the situation awareness capability is a mapped environment or a domain model that may contain initial state, goal state, possible states of the vehicle, primitive actions or activities, hard and soft constraints, uncertainty (sensors and actuators), a priori knowledge, and a low- or high-definition static/dynamic map.

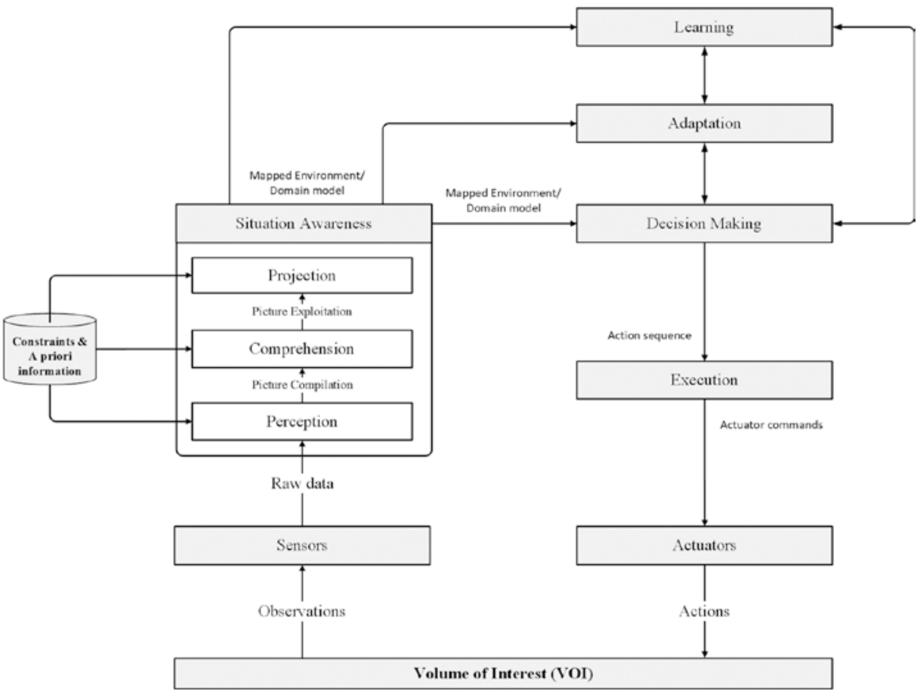

Figure 3-14. Cognitive Cycle of Autonomous Vehicles

A decision-making module is responsible for making a decision in the absence of certainty. This uncertainty, if not handled correctly, may result in wrong beliefs about its state and/or the state of the environment, resulting in wrong actions to be taken. An adaptation module enables the system to adapt its behavior based on a context extracted from the situation awareness module. Contextual information answers situation-related questions such as who, what, when, and where in order to characterize the work environment and the system's agents in terms of location, identity, activity, time, and status. Adaptation can take the form of changing role assignments or coordination mode or replanning, plan repair, and control the use of the sensing and acting resources in a manner that synergistically improves the process of data gathering and ultimately enhances situation awareness and decision-making. Learning from previous experience is a crucial feature for autonomous systems. A learning module can be designed to allow the system to learn new tasks or to automate repetitive processes and to provide smart guidance to a human whenever needed.

Let's consider motion planning as an example of a specific task of a self-driving vehicle. Motion planning is a complex activity that determines a future course of actions/activities for a self-driving vehicle to drive itself from an initial state to a specified goal state. Planning often involves reasoning under uncertainty, especially in unstructured, dynamic, and partially observable environments. To plan the motion properly, the autonomous vehicle must compute a collision-free optimal path from the start position to the given goal position, amid a collection of obstacles. While path planning focuses on the spatial aspects of the motion, trajectory planning includes spatiotemporal aspects related to how to move based on trajectory, velocity, time, and kinematics, taking into consideration the mechanical limitations of the vehicle. In the context of motion planning, the decision-making module represents the planning entity that takes the mapped environment/domain model as an input and generates a plan using a planning method/solver as illustrated in Figure 3-15. These solvers can be based on discrete planning (e.g., forward search and backward search), combinatorial planning (e.g., exact and approximate cell decomposition, Voronoi diagrams, visibility graph, freeway net and silhouette), sampling-based motion planning (e.g., rapidly exploring random trees and probabilistic road maps), potential field methods, metaheuristics, decision-theoretic planning, or hybrid approaches.

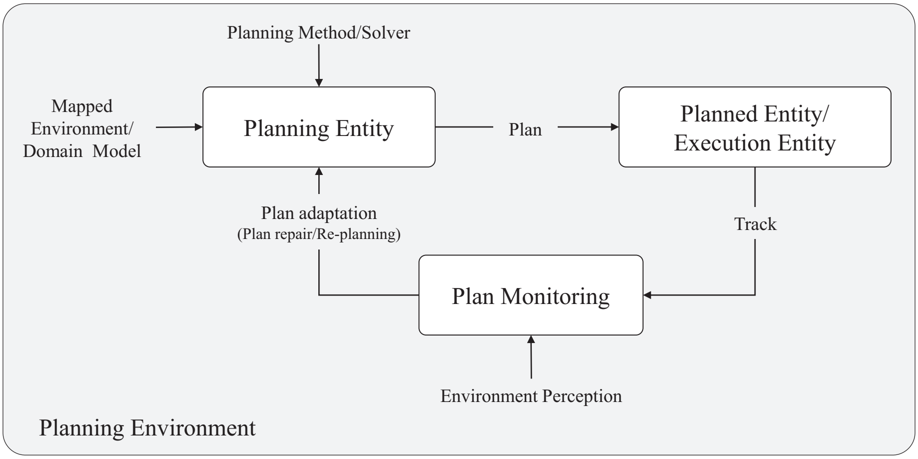

Figure 3-15. Adaptive Motion Planning

The plan is then sent to the execution module or planned entity to generate the actuation commands to be sent to the vehicle actuators. The execution of the plan can be continuously monitored by the situation awareness capability, and the adaptation capability adapts the plan whenever necessary by plan repair or a replanning algorithm. The learning capability continuously learns from examples and/or from interaction to improve future decisions.

The US Defense Advanced Research Projects Agency (DARPA) spawned automated driving vehicles through the DARPA Grand Challenge, which occurred for the first time in March 13, 2004, targeting mainly the mobile robotics community. Since then, autonomous vehicles have received an increasing amount of attention from academia, government laboratories, industry, and venture capitalists due to their wide applicability in many potential domains including smart mobility. Other competitions have been established to further advance the research and development in this area such as the AutoDrive Challenge, CARNET Autonomous Driving Challenge, and Indy Autonomous Challenge (IAC).

Several open source tools and datasets initiated in the robotics labs play crucial roles in accelerating the innovation momentum in the area of smart mobility. Examples of open source tools include Lightweight Communications and Marshalling (LCM) developed at MIT for the DARPA Urban Challenge, Robot Operating System (ROS) developed initially by two PhD students in the Robotics Laboratory at Stanford University, and the CARLA open source simulator developed by Computer Vision Center, Barcelona, in collaboration with Toyota Research Institute and Intel Labs. Open datasets include Berkeley DeepDrive, Oxford Radar RobotCar Dataset, MIT DARPA Urban Challenge Dataset, KITTI Vision, Joint Attention in Autonomous Driving (JAAD), The Zurich Urban Micro Aerial Vehicle Dataset, Robotics 2D-Laser Datasets, Wurzburg and Osnabruck Robotic 3D Scan Repository, and KAIST Urban Dataset.

3.8. Electrification

People and freight transportation is the second largest source of CO_2 emissions worldwide and the largest source in the United States. Electrification is the process of decarbonizing transportation by powering passenger vehicles and freight vehicles by electricity as a replacement for fossil fuels (coal, oil, and natural gas). Electric vehicles can be classified based on powertrain options into battery-electric vehicles (BEVs), fuel cell vehicles (FCVs or FCEVs), or hydrogen-electric combination. Both hydrogen and electric technologies are older than the combustion system. Humphry Davy demonstrated the principle of what became fuel cells in 1801, and William Grive invented in 1839 the first fueled cell called the "gas battery." The Dutch professor Sibrandus Stratingh and the instrument maker Christopher Becker presented in 1835 an all-electric tricycle equipped with one of the first electric batteries. The General Motors EV1 was the first mass-produced and purpose-designed electric vehicle of the modern era from a major automaker. Electric powertrains have some advantages over hydrogen fuel cell technology in terms of energy efficiency and the widespread availability of charging stations.

Hydrogen fuel cell technology provides faster refueling time and longer driving range compared to fully electric technology. However, battery and charging technologies have rapidly been improving charging times. GM's Ultium energy options range from 50 to 200 kWh, which could enable a GM-estimated range up to 650 km or more on a full charge with 0–96 km/hr acceleration as low as 3 seconds. Fast and ultra-fast charger can recharge an EV in minutes. For example, the charge rate of a DC fast charger is $\sim$ 300 km/hr for charging load less than 90 kW. Curbside cab charging using inductive charging technology is getting popular as well. Charging pads route enough energy to an electric vehicle's batteries to add about 80 kilometers of range for every 15 minutes the car spends hovering over the inductive coils—with no physical plugs or human hookup required (Ulrich, 2020). Battery swapping could be revived specially for MaaS and shared mobility services. San Francisco-based Ample has brought electric vehicle battery swapping to the U.S. This company uses modular batteries and currently focuses on fleet vehicles. Bloomberg reports that the Chinese government is stepping up efforts to establish common industry-wide standards that would allow drivers to swap out EV batteries in a matter of about three minutes.[6]

Table 3-3 shows a detailed comparison between BEV (battery-electric vehicle), BEV + REx (battery-electric vehicle + range extender), FCEV (fuel cell electric

[6] https://bloom.bg/2YYOeMR

vehicle), PHEV (plug-in hybrid electric vehicle), and HEV (hybrid electric vehicle).

There is another debate around how green EVs are. Despite the absence of on-the-road emission, battery and vehicle manufacturing makes EVs not as green as they should be.

Important To ensure that e-cars are zero emission in the full sense of the word, their electricity must come from renewable sources and not, for example, coal-fired power plants, while production of the battery must also be CO2 neutral (Infineon, 2018).

This arises the need for more optimized production processes using renewable sources, reducing or eliminating the use of materials like cobalt and lithium, more use of recycled materials, creation of new types of batteries and new materials, and better ways of battery use and recycling. The recycling rates of Li-ion batteries (LIBs) in the European Union and the United States are still less than 5% (Sommerville et al., 2020; Nguyen and Oh, 2020). Moreover, more public/highway and workplace stations should be available as most of the EV owners charge their vehicles at home. Allocation of public charging stations should be optimized for better road coverage. The global initiative CharIN[7] aims at developing Combined Charging System (CCS) as the standard for charging BEVs of all kinds.

Table 3-3. EV Taxonomy | Data Source: OneWedge

Property	BEV	BEV+REx	FCEV	PHEV	HEV
Example	Chevy Bolt	BMW i3	Toyota Mirai	Mini Countryman	Toyota Prius
Energy efficiency	73%	73%⟷20%	22%	60%⟷17%	54%⟷15%
Transmission	NO	NO	NO	YES	YES
Gearshift	NO	NO	NO	YES	YES
Engine	AC Induction/ synchronous	AC Synchronous	AC Synchronous	AC Synchronous	AC Synchronous
Emissions of CO_2	-66%	-66%⟷–8%	-50%	-58%⟷+2%	-57% ⟷ +11%

[7] www.charinev.org/

Several initiatives are taking place nowadays toward zero-emission cities through phase-out of fossil fuel vehicles, a.k.a. banning gas cars or banning petrol cars or the petrol and diesel car ban (Burch and Gilchrist, 2018; Muoio, 2017; Oki, 2020). Figure 3-16 shows the status of the ICE vehicle phase-out in different countries.

More than 14 countries and over 20 cities around the world have proposed adopting electrification and banning the sale of passenger vehicles (primarily cars and buses) powered by fossil fuels such as petrol, liquefied petroleum gas, and diesel at some time in the future (Outlook, IEA Global EV, 2020; Burch and Gilchrist, 2018). For example, Norway's government has decreed that all new cars must be zero emissions by 2025 (Ulrich, 2020). France plans to ban sales of petrol and diesel cars by 2040 (Chrisafis and Vaughan, 2017). Canada adopts electrification as a way to decarbonizing the transportation sector and transitioning to a low-carbon future. The government of Canada has set ambitious federal targets for zero-emission vehicles (ZEVs) reaching 10% of light-duty vehicle (LDV) sales per year by 2025, 30% by 2030, and 100% by 2040.

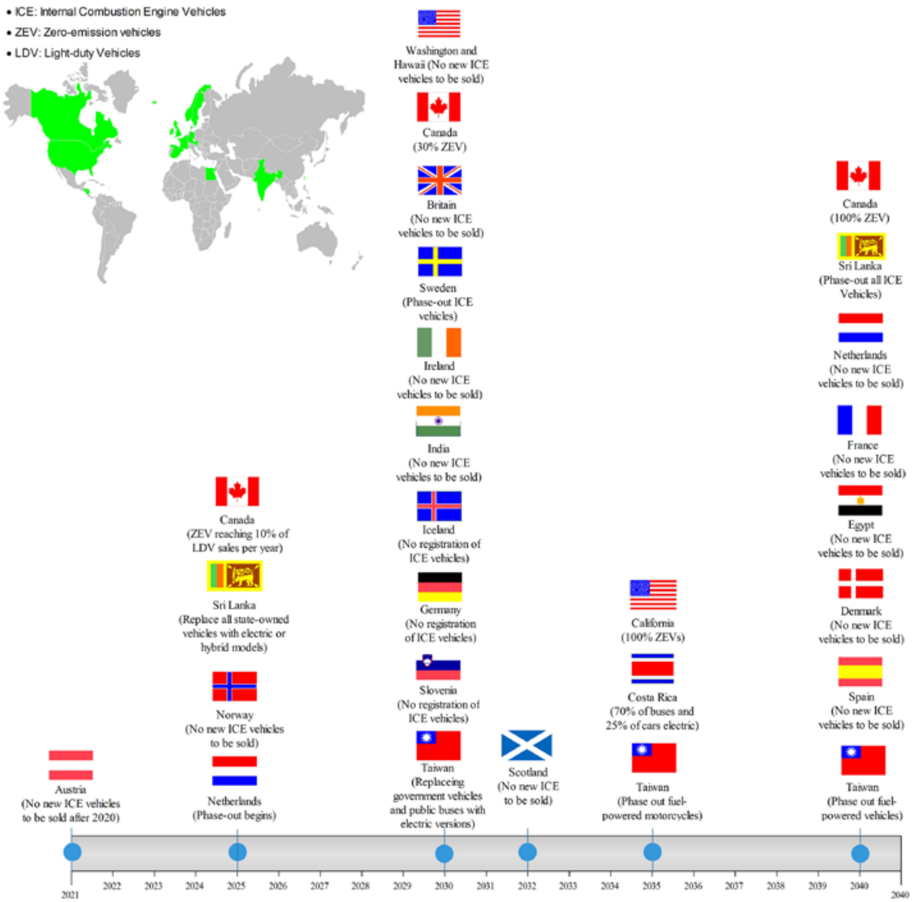

Figure 3-16. Status of ICE Vehicle Phase-Out | Data Source (Burch and Gilchrist, 2018) with Updates

3.9. Summary

In this chapter, we discussed several core building blocks of the existing and possibly emerging smart mobility systems and services. The discussed technologies include Position, Navigation, and Timing (PNT), Geographic Information System (GIS), wireless communication, mobile cloud computing, blockchain, Internet of Things (IoT), Artificial Intelligence (AI), robotics, and electrification. These technologies are not exhaustive and should be considered as examples of technologies that can be foundational in developing smart mobility services. The following chapter discusses a number of potential technology enablers for smart mobility that have been made available based on the foundational technologies discussed in this chapter.

CHAPTER

4

Smart Mobility: Technology Enablers

Evolutionary and revolutionary technology enablers provide the potential of improving existing processes and creating new and sometimes disruptive business models and services. In the context of smart mobility, these technologies may include intelligent infrastructure, connected mobility, automated mobility, e-mobility, micromobility, active/soft mobility, inclusive mobility, and Context Awareness Systems (CAS). The following sections explain these technology enablers.

4.1. Intelligent Infrastructure

Mobility infrastructure is required to accommodate existing and emerging personal and shared mobility systems and to facilitate the proper management of these systems. Examples of this supportive infrastructure include intelligent transportation systems, smart intersections, high-quality cycling infrastructure such as cycle highways (a.k.a. bicycle freeways or superhighways), smart parking, charging infrastructure, and smart pavement. In this section, intelligent

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transportation systems, smart intersections, and smart pavement are given as examples of intelligent infrastructure required as technology enablers for smart mobility systems and services.

Intelligent transportation systems (ITSs) or road telematics is an essential part of the infrastructure required for the proper operation and management of smart mobility systems. According to Williams Sale Partnership (WSP), ITS is "a combination of leading-edge information and communication technologies used in transportation and traffic management systems to improve the safety, efficiency, and sustainability of transportation networks, to reduce traffic congestion and to enhance drivers' experiences."[1] Major categories of ITS include (French and Chen, 1999)

- **Advanced Traffic Management Systems (ATMS)**: Adaptive traffic signal controls, automatic incident detection, regional traffic control, electronic toll collection, emission sensing, and so on.
- **Advanced Public Transportation Systems (APTS)**: Automatic vehicle location, signal preemption, smart cards for fare collection, dynamic ridesharing, and so on.
- **Advanced Traveler Information System (ATIS)**: Motorist information, dynamic route guidance, pre-trip planning, in-vehicle signing, and so on.
- **Advanced Vehicle Safety Systems (AVSS)**: Intelligent cruise control, collision warning, collision avoidance, night vision, platooning, and so on.
- **Commercial Vehicle Operation (CVO)**: Weigh-in-motion or weighing-in-motion (WIM), automatic vehicle classification, fleet management, international border crossing, and so on.

According to the European Commission,[2] ITS can help in reducing congestion through assistance systems and information services such as dynamic traffic management and the use of navigation systems. It also reduces fatalities and traffic-related injuries through automatic calls to emergency services and transmission of location data from the accident scene that can drastically cut response time of emergency services and reduce road fatalities by about 5–10% and result in less severe injuries. ITS has also the potential to reduce emissions by 10–20% and save energy through better demand management including the use of road charging and access management. Time-dependent

[1] www.wsp.com/en-CA/services/intelligent-transportation-systems-its
[2] https://ec.europa.eu/transport/themes/its/

dynamic trip pricing and road usage–based charging schemes are emerging techniques to control the access to the infrastructure in such a way that will minimize congestion and maximize society and environmental benefits. Several companies are offering Tolling-as-a-Service (TaaS) systems that dynamically charge road tolls. For example, Blissway's system includes route planning, vehicle and occupant verification, and toll payments. Tolls are calculated based on time saved and the number of vehicle occupants and are updated if the actual time savings differs from the estimate. The Canadian company IMS has recently partnered with transport policy makers to deploy usage-based schemes in Oregon, Utah, Washington, and California.

Important According to Precedence Research, the global intelligent transportation system (ITS) market size is expected to reach US$ 47.89 Bn by 2030, growing at a CAGR of 6.3%.

An important integral part of ITS for urban mobility is smart/intelligent intersection. The main objective of smart intersection is to protect vulnerable road users such as pedestrians and cyclists especially in busy intersections and in dense urban areas. Smart intersections integrate different sets of sensors, communication modules (e.g., DSRC roadside units or C-V2X micro cells), and data acquisition and processing modules on edge or on the cloud. Smart intersections can alert or prevent left-turning cars from running head-on into traffic that approaches from behind an occlusion. Smart intersections are also an enabler for cooperative control like flocking and platooning for connected, autonomous, shared, and electric (CASE) vehicles. For example, the automated network fundamental diagram (ANFD) is presented as a macro-level modeling tool for urban networks with smart intersections (Amirgholy et al., 2019).

Smart pavement has the potential to revolutionize the way our roads are built and financed. This technology offers radio-connected sensors being embedded in a road to constantly monitor and report the pavement's changing condition, installing two-way WiFi transmitters in the roadbed to offer enhanced commercial broadband services to vehicles and adjoining businesses/residences, and charging electric cars as they drive along, thus reducing the need for off-road recharging stops (Careless, 2017). Moreover, smart pavement can provide continuous traffic and road condition information to drivers or to automated driving vehicles and can inform authorities of accidents and other hazardous conditions. According to *The Denver Post*,[3] Colorado has announced that it will become the first city in the United States to implement "smart pavement" as part of its preparation for the arrival of autonomous vehicles and sensor-linked standard vehicles that can identify and warn drivers of hazardous conditions and sharp curves ahead.

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[3]www.denverpost.com/2018/05/30/us-285-smart-pavement-technology/

4.2. Connected Mobility

Connected mobility creates new data-rich environments and is an enabler for many applications and services that will make our roads safer, less congested, and more eco-friendly. Connected mobility is an enabler for features like real-time navigation and routing, traffic information, safety warnings, accident avoidance, advanced driver assistance systems (ADAS), and automated driving systems (ADS). Imagine, for instance, features that warn you before changing the land because of an upcoming car in your blind spot that may result in imminent crash; alert you to a hazard ahead such as an obstacle, crossing pedestrian/cyclist or stopped car, or work zone or icy road; provide remote diagnostics, trouble code notification, and repair services; deliver real-time updated information about traffic and point of interest such as a mall; help you find open parking spaces and gas/charging stations; and facilitate online shopping.

The wide umbrella of connectivity is vehicle-to-anything (V2X) that secures sharing of information seamlessly between the vehicle and everything in the right format at the right time. Here, the concept of vehicle is extended to include any mobility platform used for transporting people or goods on land, sea, or air such as cars, trucks, bikes, e-scooters, air/river taxis, automated people movers, and so on. The connectivity forms include the following:

- **Vehicle-to-Occupant (V2O)**: An occupant can be a driver or a passenger of a mobility platform. V2O enables features like BLE/UWB-enabled phone-as-a-key; in-vehicle connectivity services for work, play, and commerce; driving error recognition and prediction; and quantifying the quality of experience. V2O can be extended to include customer connectedness that includes not only direct human involvement with WiFi, 4G, and now 5G technology through various interface devices such as smartphones, gaming consoles, and augmented reality/virtual reality headsets but also the connected delivery of insight from a diversely growing number of things. For example, connected healthcare devices and personal wearables can tell occupants about the experiences they have with the vehicle and in the environment around them (Whitelock, 2019).
- **Vehicle–to–Vulnerable Road User (V2VRU)**: VRUs include pedestrians and cyclists as well as motorcyclists and persons with disabilities or reduced mobility. V2VRU can be an enabler for VRU detection, localization, and crossing intention and motion behavior recognition.

- **Vehicle-to-Vehicle (V2V)**: For applications like post-crash warning, pre-crash warning, cooperative collision warning, cooperative forward collision warning, lane change warning, vehicle-based road condition warning, visibility enhancer, wrong way driver warning, intersection movement assist, blind spot warning, communication relaying in case of emergency, smart cargo companions, last-mile delivery systems, cooperative adaptive cruise control, cooperative automation, fleet management systems, and self-organized autonomous vehicles. V2V allows all vehicles to move in a coordinated fashion, reducing stop-and-go congestion and emergency maneuvers (Hedlund and North, 2018). Different communication technologies have been proposed and implemented to facilitate vehicle-to-vehicle (V2V) communication, sensor data sharing, cooperative perception, and safety applications (Edison, 2019; Higuchi et al., 2019; Thota et al., 2019).
- **Vehicle-to-Environment (V2E)**: For applications such as road condition monitoring, traffic sign and light recognition, driving risk prediction, and perimeter monitoring systems. Slow and near-real-time infrastructure and environmental sensing can be also achieved by connected vehicles. Slow-changing infrastructure sensing includes, but is not limited to, road roughness or estimation of the International Roughness Index, bank angle, lane marking quality, potholes, speed bumps, and so on (Nguyen et al., 2019). Examples of near-real-time infrastructure sensing conditions include snow coverage, dust coverage, oil spill detection, and so on.
- **Vehicle-to-Infrastructure (V2I)**: For road condition warning, SOS services, work zone warning, emergency vehicle signal preemption, intersection collision warning, in-vehicle AMBER alert, remote diagnostics and repair, pedestrian crossing information, red light warning, pedestrian detection and warning, bicycle detection and warning, no left-hand turn warning, traffic condition monitoring, weather condition, traffic light management system, interaction management system, parking management system, and teleoperation in case of malfunctioning self-driving cars. For example, GM's OnStar services provide automatic collision notification, SOS emergency assistance, enhanced roadside assistance,

monthly vehicle health report, automatic diagnostic trouble code notification, service link, maintenance reminder, driving information, and on-demand diagnostics.

- **Vehicle-to-Network (V2N)**: For disabled roadside vehicle warning, security credential management system, multimodel mobility systems, dynamic on-demand mobility systems and services, cloud-based crowdsensing services, real-time traffic monitoring, and bringing attractive consumer experiences into the cabin to foster brand loyalty.

Figure 4-1 illustrates how different forms of connectivity such as V2VRU, V2V, and V2I can play a role in a post-crash safety warning scenario using DSRC and C-V2X wireless communication technologies. In this scenario, a vehicle ahead of the way is able to notify other vehicles about incidents that lie ahead or an alarming situation such as emergency electronic brake light ahead warning or forward collision avoidance (Peng et al., 2019).

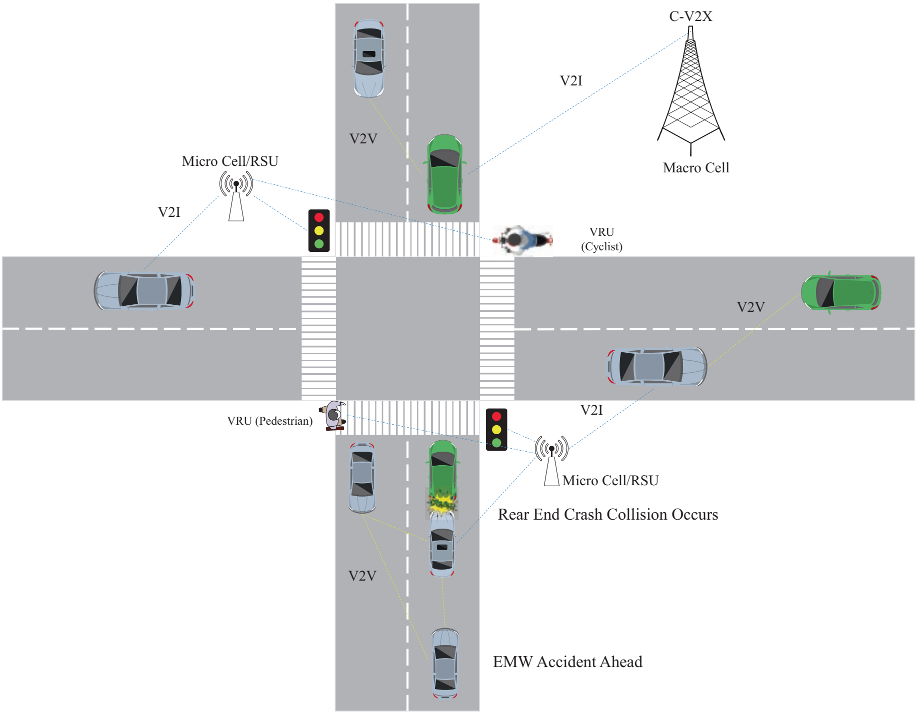

Figure 4-1. Post-Crash Safety Warning Scenario

As mentioned in the previous chapter, the FCC has ruled new regulations in November 2020 to reallocate the 5.850–5.925 GHz (i.e., 5.9 GHz) spectrum band dedicated for DSRC standard operations since 1999. The spectrum reallocation announced by the FCC comes as a drastic measure toward the slow deployment of the DSRC technology. The existing 75 MHz safety spectrum will be subdivided into two bandwidth allocations. The upper band 30 MHz ranging from 5.850 to 5.925 GHz will no longer support DSRC and will be instead reassigned to advance and speed up the deployment of cellular vehicle-to-everything (C-V2X) technology.

4.3. Automated Mobility

The WHO considered human error as the single largest cause of all collisions today and a major factor in more than 90% of fatal crashes (World Health Organization, 2018). Automated mobility aims at eliminating or reducing these injuries and fatalities, improving access to mobility for those who currently cannot drive due to age or disability, and creating new business models such as passenger economy.

4.3.1. Self-Driving Cars vs. Self-Flying Planes

Automation of planes began 9 years after the Wright brothers took flight in 1903. The first aircraft autopilot was developed by Sperry Corporation in 1912. More than a hundred years ago, the first autopilot models were developed, installed, and used in aircraft. However, car autopilots are still not as popular as plane autopilots.

Warning "Automated driving is a bit more challenging technically than we originally thought" (Hakan Samuelsson, Volvo CEO).

The main reason for that is the nature of the operation environment. Environments where planes operate are relatively static, predictable, structured, and observable, while cars and other urban mobility vehicles' operating environments are highly dynamic, unstructured, and partially observable with so many corners/edge cases and unknown unknowns. The same applies to closed-system automated rapid transit systems (e.g. subways and automated people movers) and trains that can be fully automated due to the static, predictable, structured, and observable nature of the environment they operate in. Figure 4-2 shows the relation between the domain knowledge and the meta-knowledge we have in the automated-driving vehicles' environments.

		Domain Knowledge (We have or don't have)	
		Knowns	Unknowns
Meta-knowledge (We know, or don't know about the state)	Known	Known-Knowns (information that we have and know that we have)	Known-Unknowns (information that we don't have and know that we lack)
	Unknown	Unknown-Knowns (information that we have but don't know we have)	Unknown-Unknowns (information that is relevant, but we don't know that we lack)

Uncertainty

Figure 4-2. Meta-knowledge vs. Domain Knowledge

Known knowns represent information that we have and know that we have. For example, the ADS ability to recognize traffic signs and lights can be seen as a known known. Unknown knowns are the information that we have but don't know we have. Known unknowns represent information that we do not have and we know that we lack. Adversarial and edge/corner cases can be considered as known unknowns as we know most of these cases but we don't know how to deal with them. Adversarial use cases are those cases that can confuse the model due to their similarity to target cases. Examples of adversarial cases include a plastic bag filled with air or a fake pothole/speed bump or air puppet inflatable balloon in a pedestrian crosswalk or banners with real-size human pictures. These objects can be wrongly interpreted by an object recognition system as an obstacle that needs to be avoided. Examples of edge/corner cases include, but are not limited to, a large animal/deer that suddenly leaps on the hood of the car, unusual road obstacles like sheep herds, strange horse-drawn carriages, extreme weather conditions, and so on. Unknown unknowns are the information that is relevant but we do not know and we do not know that we lack. An example is the sensitivity to unknown perturbation. For instance, Boeing 737 MAX has a computer-controlled stability system called MCAS to prevent stalling during flight. The impact of a malfunctioning angle-of-attack sensor used by MCAS was an unknown unknown before the two plane crashes of Lion Air Flight 610 in 2018 and Ethiopian Airlines Flight 302 in 2019. When the system failed, MCAS prevented the pilot from doing the right thing as the system was designed to comply with safety measures. This resulted in the Boeing 737 MAX air disaster saga.

Given the fact that the driving task is a highly repetitive and reactive activity, humans of all levels of intellectual capabilities can get driving licenses especially if they drive in known areas. In his talk entitled "From System 1 Deep Learning to System 2 Deep Learning," presented at the Conference on Neural Information Processing Systems (NeurIPS 2019), Yoshua Bengio explained the difference between "System 1" and "System 2" cognition. System 1 is "the kinds of things that we do intuitively, unconsciously, that we cannot explain verbally, in the case of behavior, things that are habitual," Bengio said. While System 1 operates automatically and quickly, with little or no effort and no sense of voluntary control, System 2 allocates attention to the effortful mental activities that demand it, including complex computations. The operations of System 2 are often associated with the subjective experience of agency, choice, and concentration (Kahneman, 2011). Here's how Bengio explains the difference between System 1 and System 2. Imagine driving in a familiar neighborhood. You can usually navigate the area subconsciously, using visual cues that you have seen hundreds of times. You do not need to follow directions. You might even carry out a conversation with other passengers without focusing too much on your driving. However, when you move to a new area, where you don't know the streets and the sights are new, you must focus more on the street signs, use maps, and get help from other indicators to find your destination. In the known area scenario, you use System 1 cognition, and you will have to switch to System 2 cognition in the unknown area scenario to be able to drive the car. Relying on System 1 probably is the reason behind having most accidents happening on familiar everyday journeys. Mimicking or reverse-engineering these System 1 and System 2 cognitive functions to build ADSs able to navigate through dynamic, unstructured, and partially observable environments is quite challenging. It is not surprising that the average lines of software code in modern luxury vehicles are much larger compared to types of aircraft. For example, while the F-22 US Air Force jet fighter has 1.7 million lines of code and Boeing 787 Dreamliner has 6.5 million lines of code, a modern luxury vehicle has more than 100 million lines of code (Wise, 2016). These modern vehicles are equipped with Internet connectivity, sensors and actuators, and over 50 microcomputers making these vehicles be like "super computers or de facto IT devices on wheels." However, as the lines of software code in vehicles increase, so does the potential for software errors and related vulnerabilities (Wise, 2016).

Urban air mobility (UAM) platforms for people and cargo transportation explained in the next chapter share the complexity of the environment with self-driving vehicles with additional technical challenges of aviation such as stability and regulatory aspects such as noise pollution and visual disruption.

4.3.2. Automated Driving

Similar to the levels of control explained in the previous chapter, the SAE (Society of Automotive Engineers) International (SAE On-Road Automated Vehicle Standards Committee and others, 2018) defines six levels of driving automation (Table 4-1). In their standards such as SAE J3016 (Taxonomy and Definitions), SAE J3018 (Safe Testing of Highly Automated Vehicles on Public Roads), and SAE J3131 (Automated Driving Reference Architecture), SAE does not use the term autonomous and uses instead the term automated driving to reflect the fact that even the most advanced automated driving systems are not self-governing. The difference between automated systems and autonomous systems was highlighted in the previous chapter.

Automated driving systems (ADSs) include level 3 (Low), level 4 (Medium), and level 5 (High). The term highly automated vehicle (HAV) sometimes is used instead of ADS. Level 5 is the driverless full vehicle autonomy level in all operational design domains (ODDs) that can be managed by a human driver. ODD is the definition of where and when an ADS is designed to operate. ODD would include the following information at a minimum to define each ADS's capability limits/boundaries:

- Roadway types (interstate, local, contained roadways such as residential communities, universities, technology parks, retirement and leisure) on which the ADS is intended to operate safely
- Geographic area (city, mountain, desert, etc.)
- Speed range
- Environmental conditions in which the ADS will operate (weather, daytime/nighttime, etc.)
- Other domain constraints

SAE International and ISO collaborate to update and refine SAE levels of driving Automation as a way to reduce misinterpretation of concepts. The most notable recently announced changes include naming SAE Level 1 and 2 as "Driver Support Systems" and SAE Levels 3-5 as "Automated Driving Systems". Additional terms and definitions have been also added such as remote assistance and remote driving. Remote assistant and remote driver are the terms given to the users who perform these functions. Definitions for vehicle types have been grouped together by Conventional Vehicle, Dual-mode Vehicle and ADS-dedicated Vehicle. Further clarity on the differences between SAE Level 3 and SAE Level 4 was provided including the role of the fallback-ready user, the possibility of some automated fallback at SAE Level 3, and the possibility of some alerts to in-vehicle users at SAE Level 4. Explanation for how classifications of sustained driving automation fit into the broader context of driver assistance and active safety features is also added. For more information about on-road driving automation levels and potential objective test methods that could be used as a framework for evaluating emerging and future driving automation features, you can refer to Tellis et al. (2016).

4.3.3. Automated Driving and Safety

Humans usually apply a set of defensive driving rules to drive safely. One example, the "Smith System," is based on five key rules called Smith5Keys. These five principles, rules, or keys are "aim high in steering," "get the big picture," "keep your eyes moving," "leave yourself an out," and "make sure they see you." These rules provide drivers with the knowledge and skills to create three important things while driving: space to maneuver the vehicle away from conflict, visibility to detect danger and the potential for conflict with another vehicle or fixed object early, and time to react to volatile and complex driving environments. Other general principles defined in Standard Safe Practices for Motor Vehicle Operations (ANSI/ASSE Z15.1) include maintaining a safe following distance, driving safely considering (adjusting for) weather and/or road conditions, and adjusting your speed before entering a bend, in order to avoid applying the brakes in the middle of a bend (Hinderks et al., 2018). Self-driving vehicles will need governing rules for defensive driving as well. Mobileye introduced a model-based approach to safety entitled Responsibility-Sensitive Safety (RSS) (Shalev-Shwartz et al., 2017). RSS highlights five safety rules an automated driving vehicle should be able to follow. These five rules include safe distance (i.e., the self-driving vehicle should not hit the vehicle in front), cutting in (the self-driving vehicle should be able to identify when lateral safety may be compromised by a driver unsafely crossing into its lane), right of way (the self-driving vehicle should be able to protect itself against human drivers who do not properly adhere to the right of way rules), limited visibility (be cautious in areas with limited visibility), and avoiding crashes (the self-driving vehicle should avoid a crash without causing another one).

Table 4-1. SAE Levels of Automated Driving

Level	Name	Automated System Role	Human Role
0	No automation	None	All driving functions
1	Driver assistance (feet-off)	Driver-assist features including adaptive cruise control, preemptive braking or automatic emergency brake, lane centering, parking assist, driver observation, and alerts	Responsible for all core driving functions
2	Partial automation (hands-off)	Partial driving automation such as steering, acceleration, and deceleration (e.g., Cadillac Super Cruise, Audi Traffic Jam Assist, Mercedes-Benz Driver Assistance Systems, Tesla Autopilot, Volvo Pilot Assist)	Responsible for monitoring roadway environment, ready to assume control with or without system warning
3	Conditional automation (eyes-off)	Most driving functions and roadway monitoring are automated, for example, valet parking. System-designated request for human intervention and driver necessity	State of ongoing readiness to assume control and intervene in response to system request
4	High automation (mind-off)	All driving and monitoring functions are automated, for example, urban pilot. Operation limited to selective geo-fenced environments (e.g., defined shuttle routes)	Human control unnecessary. Steering, pedals, and gear shifting generally unavailable
5	Full automation (robotic chauffeur)	All driving functions and environments without a human driver (e.g., robot taxi and unmanned/zero-occupant vehicles or ZOVs)	Human input to navigation but without any vehicle control. Possible opt-in or opt-out by human operator

According to NHTSA, vehicles have experienced five eras of safety. Safety and convenience features such as cruise control, seat belts, and antilock brakes were introduced in the period from 1950 to 2000 followed by introducing advanced safety features such as electronic stability control, blind spot detection, forward collision warning, and lane departure warning in 2000–2010. Advanced driver assistance features such as rear-view video systems, automatic emergency braking, pedestrian automatic emergency braking, rear automatic emergency braking, rear cross-traffic alert, and lane centering assist were widely deployed in 2010–2016. Recently, partially automated safety features such as lane keeping assist, adaptive cruise control, traffic jam assist, and self-park have started to emerge. Fully automated safety features and highway autopilots that comply with safety standards are expected to be available in the next decades according to NHTSA. Vehicle safety standards are discussed in Chapter 2. With these advanced safety features, automated vehicles have the potential to remove human error from the crash equation saving lives and reducing injuries. However, it is not well known yet the best way to deal with some safety issues of self-driving vehicles that may arise due to errors committed by the vehicle itself such as sensing errors, perception errors, decision errors, or action errors and lack of the ability to handle all mishaps caused by other human driver errors in mixed traffic scenarios or lack of the ability to deal with vulnerable road users who do not follow traffic rules.

Several safety ratings are used to evaluate different safety aspects of vehicles. For example, the 5-Star Safety Ratings Program evaluates how vehicles perform in crash tests. Insurance Institute for Highway Safety (IIHS) tests evaluate two aspects of safety, namely, crashworthiness (i.e., how well a vehicle protects its occupants in a crash) and crash avoidance and mitigation—technology that can prevent a crash or lessen its severity. Euro NCAP has also created the five-star safety rating system to help consumers, their families, and businesses compare vehicles more easily and to help them identify the safest choice for their needs. These safety ratings keep evolving to match with capabilities of automated driving vehicles at different levels of automation.

4.3.4. Data-Driven Approach and Self-Driving Vehicle Safety

According to Mobileye, safety and runtime efficiency can only be guaranteed if the RSS model is integrated with semantic-based decision-making as a pure data-driven approach is infeasible to achieve this target. In order to prove the infeasibility of a pure data-driven approach, Mobileye gives the following example:

Important Assume that probability ρ of fatality per 1 hour of driving$=10^{-6}$, which is equivalent to ~35,000 fatalities per year. For society to accept an ADS, desired ρ would be 10^{-9}, which is equivalent to ~35 fatalities per year. And to guarantee probability of an event/hour is ρ, an ADS must drive $1/\rho = 10^9$ hours. This travel duration is $\approx$ 30 B mile assuming average speed of 30 mph.

Based on findings of the RAND Corporation report "Driving to Safety" (Kalra and Paddock, 2016), Mobileye summarizes the miles and years needed to demonstrate autonomous vehicle reliability in Table 4-2.

Table 4-2. Miles and Years Needed to Demonstrate ADS Reliability According to Mobileye

In Order to Prove Fatality Rate…	We'd Need to Drive…	100 Cars Driving 24/7/365 Would Take…
Equals human drivers	~300 M miles	Over a decade (13 years)
Reduced by 90%	~3 B miles	Over a century (130 years)
Reduced by 99%	~30 B miles	Over a millennium (1,300 years)

Interestingly, Mobileye predicted the data and equipment cost of driving 30 billion miles to achieve full autonomy capability.

Warning As per data cost, an ADS with surround LiDAR, radar, and cameras generates ~5 terabytes per hour, so 10^9 hours of driving will generate 5 M petabytes that would cost ≈ $2 trillion. As per equipment cost, 30 B mile is ≈ 4 B cars operating 20 hours per day for 1 year. If every test car costs $100,000, the total equipment cost would be ≈ $400 billion.

Reducing the complexity of the work environments or targeting restricted operational design domains enables the successful deployment of ADSs in a number of industries. For example, ADSs are used by mining companies to haul gravel, autonomous boats for shipping, and self-driving tractors to seed, plow, and spray vast, unpopulated agricultural fields by farmers. Self-driving vehicles are also deployed in distribution centers and factories as specialized automated vehicles in warehouse pick and place operation and in resorts and airports as driverless shuttles carrying passengers back and forth on set tracks at a speed of 24 km/h (Lipson and Kurman, 2016).

4.3.5. Automated Driving and Social Interaction

Lipson and Kurman highlighted in (Lipson and Kurman, 2016) a challenge for self-driving vehicles in urban environments related to the need for a social interaction with vulnerable road users like pedestrians and cyclists. This can also be extended to first responders (law enforcement officers) who direct traffic in case of an incident/accident and a construction worker who holds a "STOP" and "SLOW" signage loosely in their left hand and waves vehicles through with their right asking the vehicles to stop temporarily or to slow down the speed or a parking attendant waving in the lane next to the vehicle into a garage. This social interaction, mainly through nonverbal communication using eye contact, body movement, and hand gestures, plays a crucial role in securing the safety of vulnerable road users. Mimicking this social interaction and following formal and informal rules of interaction represent challenges for ADSs. Understanding gestures made by people on streets is addressed in (Weaver, 2020).

In this system, nonoptical motion capture technology and machine learning modeling are used to develop a gesture recognition system for GM Cruise's autonomous vehicles. This system is able to recognize vulnerable road users' gestures such as stop, go, turn left, and turn right. The Automation and Public Safety Common Solutions (APSCS) Consortium in collaboration with the Virginia Tech Transportation Institute (VTTI) and the University of Massachusetts Traffic Safety Research Program (UMassSafe) conducted an interesting study about several emergency response scenarios for automated driving systems. This consortium consists of major automakers such as GM, Ford, Mercedes-Benz, Toyota, Honda, Hyundai, and Nissan (Terry et al., 2018). The described emergency response scenarios in this study include responding to an incident, securing an incident scene, conducting traffic direction and control, conducting a traffic stop, investigating an abandoned or unattended vehicle, and performing stabilization and patient extrication. Different direct, indirect, and informational safety interactions are considered in each of these scenarios.

4.3.6. Automated Driving and Smart Mobility

In the smart mobility domain, automated driving is not restricted to cars but can be extended to different mobility platforms for people transportation and freight delivery. These platforms include, but are not limited to, self-driving shuttles (e.g., GM's Cruise Origin), self-driving modular stores (e.g., Toyota's e-Palette), last-mile delivery (e.g., Starship, Nuro, and Robby), and first- and middle-mile delivery self-driving trucks (e.g., Embark, Tesla, TuSimple, Daimler Trucks, Waymo, Plus.ai, and Peloton). The United States, Germany, the United Kingdom, and several European countries have enacted legislation allowing autonomous vehicles to be tested on public roads. Málaga, the sixth largest city in Spain, is the first place in Europe to trial a full-size 12-meter self-driving passenger-carrying bus. This 60-passenger bus will make an eight-kilometer round trip from the city center to the port, six times daily. General Motors' Cruise plans to begin deploying its robo taxis in Dubai beginning in 2023, making Dubai the first city outside the United States where Cruise will operate. Cruise will be the exclusive robo taxi service provider in the Emirates until 2029. By 2030, Cruise and Dubai's RTA plan to have 4,000 self-driving taxis in operation. Moreover, Cruise is authorized by California Public Utilities Commission (CPUC) in June 2021 to give passengers rides in prototype robotaxis. Testing of driverless vehicles is permitted on public roads in Ontario, Canada, but under strict conditions. In early 2021, China changed the law to allow automated driving vehicles to be tested on public highways. There are also several efforts in enabling automated driving capabilities for fleets of vehicles through flocking and platooning, for example. According to Bishop Consulting, in level 1 or L1 platooning (first generation), the front driver drives normally with crash avoidance support such as connected braking and rear driver(s) steer, monitors the road, and responds to traffic. In level 4 or L4 following (second generation), the front driver drives the same way as in L1, but there will be no driver in the follower truck(s) and technology like AutoFollow is used.

ADSs are going to dramatically change the world, and there are several intended and unintended consequences of this technology. Centre for London summarized the possible urban outcomes from automated driving into decreased driving costs of public and private vehicles, increased convenience, increased delivery demands, increased congestion, improved public transport accessibility, decreased demand for parking, and decreased city walkability (Bosetti et al., 2020). However, the Centre highlighted the high uncertainty around adoption and ability to achieve full automation.

Car parking spaces could reduce by 70%, traffic lights will change or disappear, taxi fleets could reduce by 40%, cars will teach us about human behavior, and cars will teach us about the world around them (Walsh, 2020). Others with pessimistic views see that ADSs could make traffic and emissions worse (Madrigal, 2018). Select Car Leasing predicts the following consequences of ADSs (Select Car Leasing, 2018):

- Disappearance of road rage
- Increase in alcohol consumption (estimated increase in value for the alcohol industry by $62.7 billion as driving and drinking times begin to overlap)
- The replacement of ownership with usership (80% drop in consumer demand for new vehicles by 2030 as drivers move toward a subscription-based model according to a study by RethinkX)
- The legal underage driving (38% of the public would be happy for their child to ride an ADS car according to a study by the Open Roboethics Institute)
- Disappearance of car radio as passengers will spend their journey watching shows or looking at social media or working

The Capgemini Research Institute conducted a study on 5,500 consumers and 280 executives from Europe, North America, and Asia (Winkler et al., 2019). This study shows that 25% of these potential consumers would consider riding in a self-driving car in 12 months' time and 54% of them would trust an autonomous vehicle carrying non-driving family members and friends. The study also shows that 73% of consumers are most excited about the fuel efficiency offered by automated driving vehicles, closely followed by reduced emissions (71%) and saving time (50%). As a reflection of this growing optimism and trust in the technology, 52% expect the bugs to have been ironed out of the technology by 2024, to the extent that driverless cars will be their preferred mode of transport.

4.4. E-Mobility

Electric mobility or e-mobility promises environmentally friendly mobility that eliminates both emissions and noise pollution in the roads. E-mobility includes any mobility platform powered by electric motors. Examples include e-cars, e-bikes, e-scooters, e-skateboards, electric wheelchairs, eVTOL, electric shuttles/commuters, automated people movers (APMs), hyperloop, monorail trains, and so on.

Important The global e-mobility (e-car, e-scooter, e-bike, e-skateboard, e-motorcycle, and e-wheelchair) market size is expected to reach $489,316 million by 2025 and registers CAGR of 21.6% from 2019 to 2025, according to Research and Markets

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The global market for electric vehicles (EVs) is in the early stages of adoption, representing about 2% of global sales of new vehicles in 2019 (William Hughes and Abuelsamid, 2020). However, global electric car sales reached 2.3 million in 2020, an almost fourfold increase in just five years according to the World Economic Forum. In some countries like Norway, nearly 50% of new cars are now EVs, a higher percentage by far than in any other nation (Ulrich, 2020). In Norway, EV drivers enjoy a 90% discount on road tax. McKinsey's Electric Vehicle Index (EVI) shows that the global electric vehicle (battery-electric vehicles and plug-in hybrid electric vehicles) industry continues to expand rapidly (Hertzke et al., 2019). The EVI is a score from zero to five that assesses the e-mobility performance of 15 key countries around the world. China is leading the global e-mobility market.

Although the spread of and the societal acceptance for e-mobility are growing very quickly especially in the micromobility and public transit domains, there are still some challenges that face e-mobility especially in the e-car domain. These challenges or limiting factors include the high price of e-cars compared to ICE cars, lack of appealing incentives for EV purchasing, range anxiety, battery lifetime and degradation, and the availability and the interoperability of supercharging points. Infineon highlights that the attractiveness of e-mobility stands and falls by the batteries: what distance can the mobility platform cover with them, how much do they cost, and how much do they weigh (Infineon, 2018)?

There are some other safety concerns due to the lack of noise, which may impact negatively on awareness of vulnerable road users like pedestrians and cyclists. An electric vehicle driving at low speed or backing up is very quiet and can pose a danger to vulnerable road users especially sight-impaired pedestrians crossing the street. Some SAE experts say that the odds of an EV hitting a pedestrian are 19% higher compared to an ICE vehicle. Several governments in North America and Europe plan to require that electric vehicles emit automatic audible warning signals when traveling at less than 18 miles per hour in order to prevent pedestrian injuries at intersection crosswalks or when electrified vehicles are backing up.

Affordability is still one of the most significant barriers to EVs. Other electric micromobility platforms such as e-bikes, e-scooters, and e-rickshaws (see Section 4.5) especially the shared ones are much more affordable. Despite the high initial cost of EVs compared conventional internal combustion engine vehicles (ICEVs), the running cost of these vehicles is much less. According to a study conducted by the University of Michigan's Transportation Research Institute[4] in 2018, electric vehicles cost less than half as much to operate as ICE cars. This study shows that the average cost to operate an EV in the United States is $485 per year, while the average for an ICE vehicle is $1,117. Moreover, given the fact that EVs have much less moving parts compared to ICEVs, the useful lifetime of an EV is significantly longer, and the maintenance requirements are much less. The only exception is the short life span of the battery. According to InsideEVs,[5] almost all electric vehicle batteries are warrantied for at least eight years and 100,000 miles. Moreover, EVs are getting more affordable with time. According to an Electric Vehicle Market Status—Update report,[6] there will be available soon EV models with a net cost of under $30,000 (MSRP) with a range of up to 250 miles when current federal, state, and local incentives are factored in. This report also shows that EVs will reach price parity with ICEVs (based on total cost of ownership without considering any tax incentives) when battery pack prices fall below $100/kWh. While some industry experts believe this could happen as early as 2021, most believe it will happen around 2025. Several OEMs are accelerating the electrification timeline. For example, General Motors introduced a range of new EVs in 2020 including Cadillac Lyriq and the iconic American SUV Hummer EV with a plan to launch 30 EVs around the world by 2025.

Vehicle-to-grid (V2G) technology (Sovacool et al., 2020) can help in improving EV affordability as it enables EV owners to gain money through pushing the energy back from the battery of an electric car to the power grid. However, a car has to be plugged in 75% of the time to capture the potential value of V2G. Compared to the residential users, this would not be a problem for fleets like emergency response vehicles or logistics. Grid balancing, grid maintenance, distribution network interoperability, and data privacy/cybersecurity are still challenges for V2G. Regarding V2G cybersecurity, for example, data will be shared between four parties, namely, retailer/supplier, network company, fleet, and individual users. Guaranteeing transparency (why

[4] https://bit.ly/2YWD35V
[5] https://insideevs.com/news/368591/electric-car-battery-lifespan/
[6] https://bit.ly/3q33jaA

should the data be shared?), trust (with whom will the data will be shared?), and value (what are the benefits of sharing the data?) can help in the societal acceptance of V2G technology.

E-mobility should be supported by adaptive route planning and navigation algorithms, contactless payment, and energy assist apps to avoid user's range anxiety and charge anxiety. Nowadays, there are several energy assist tools available such as myChevrolet mobile app's Energy Assist, Google Automotive Services (GAS), EVNAViQ, PlugShare Trip Planner, ChargePoint, ChargeHub, EVgo, EVHotels, Chargeway, Chargemap, and Greenlots. GM Energy Assist is integrated with data from the vehicle, which enables smart planning and accurate charge time predictions. Services provided by this app include real-time charging station availability (for charging networks such as EVgo, Flo, ChargePoint, and EV Connect), payment, owner reviews and ratings of stations, and preference settings (e.g., charger type, network, and charger availability). Similarly, several apps are available for micromobility platforms such as e-bikes, e-scooters, and e-skateboards. Examples include Strava, Trailforks, Gravatron, Coach's Eye, Bike Share Toronto, WIND, HFX, and the SpinBike shared e-scooter acquired by Ford. At the EV fleet level, Ubiq platform provides predictive charging, charging as a service (ChaaS), dynamic pricing and automated fleet rebalancing.

4.5. Micromobility

Micromobility is a small, lightweight, and low-speed (below 25 km/h) mobility platform typically used for short-distance trips. Micromobility is gaining increasing popularity and can take different forms such as bikes, scooters, skateboards, and self-balancing unicycles.

Important Inkwood Research anticipates that the global micro mobility market will reach $13.27 billion by 2026, growing at a CAGR of 12.09% during the forecast period, 2021-2026.

Electric-powered platforms are called electric micromobility platforms such as e-bike, speed pedal-assist bicycle, e-scooter, electric seated scooter (also referred to as Vespa-style scooter or moped), e-skateboard, electric motorcycle (also referred to as electric two-wheeler or E2W), fun utility vehicle (FUV), e-rickshaw (also known as electric tuk-tuks or toto), Segway, and electric quadricycle/battery-powered mini car (e.g., Chevrolet EN-V 2.0).

These mobility platforms can be shared or personally owned as personal transporters. They can be used for local mobility, first-mile transportation (i.e., from home or origin of the journey to the transport system) and last-mile transportation (i.e., from the transport system to the final destination such as home, a workplace or a coffee shop), surveillance, and delivery services in places like educational institution campuses, residential compounds, shopping malls, theme parks, and airports to name just a few. For example, shared electric rickshaws have been becoming very popular in many countries especially low-income developing countries as an informal and equitable transportation system. Equitable transportation systems address the needs of previously underserved populations, enabling these groups to conveniently and affordably access destinations and opportunities (Yanocha and Allan, 2019). The affordability provided by micromobility is an attractive factor in both developed and developing countries given the fact that spending on transportation is a major household expenditure category. For example, spending on transportation is the second largest expenditure category accounting for 19.9% of total consumption, preceded by shelter budget at 29.2% and followed by food expenditures at 13.4% in 2017 according to Statistics Canada.[7]

McKinsey[8] claims that micromobility could theoretically encompass all passenger trips of less than 8 kilometers (5 miles), which account for as much as 50–60% of today's total passenger miles traveled in China, the European Union, and the United States. The Institute for Transportation and Development Policy summarizes in (Yanocha and Allan, 2019) the potential positive and negative impacts of electric micromobility like e-bikes and e-scooters in terms of access, environment, equity, affordability, efficiency, safety, and health. For example, in terms of access, electric micromobility's potential positive impacts include travel times competitive with vehicles for short trips and connections to transit and economic and social opportunities. However, demand for public parking will be increased, and infrastructure changes are required.

4.6. Active, Soft, or Zero-Impact Mobility

Aside from being popular recreational activities, walking and cycling are also efficient, affordable, environmentally friendly, and accessible means of active mobility. Shifts from motorized to non-motorized vehicles for short trips are highly encouraged in many developed countries. Moreover, Millennials or Gen Y usually choose to settle in dense urban areas that favor walking, bicycling, and other active mobility modes. Active or soft or zero-impact mobility includes non-motorized human-powered transporters such as walking, pedal bicycles, kick scooters, roller skates, skateboards, and pedal rickshaws. These mobility modes are a cheap, fun, and environmentally friendly option for first-/last-mile urban mobility. Active mobility can certainly be a step forward toward a future of sustainable mobility.

[7] https://bit.ly/3a1CZYR
[8] https://mck.co/3rQEXkK

Important According to a study undertaken by the National Collaborating Centre for Environmental Health (NCCEH), the wider benefits of walking, cycling, and other active transportation modes include reduced road congestion and greenhouse gas emissions; cheaper infrastructure, including lower maintenance costs; road safety improvements; and lower user costs compared to motorized vehicles (Reynolds et al., 2010).

The General Theory of Walkability states that a journey on foot should satisfy four main conditions: be useful, safe, comfortable, and interesting (Speck, 2014). Different walkability measures or metrics are proposed based on several factors such as presence of continuous and well-maintained sidewalks, universal access characteristics, path directness and street network connectivity, safety of at-grade crossing treatments, absence of heavy and high-speed traffic, pedestrian separation or buffering from traffic, land use density, building and land use diversity or mix, street trees and landscaping, visual interest, and a sense of place as defined under local conditions and perceived or actual security (Lo, 2009). For example, Walk Score is used to measure a city's walkability in the United States, Canada, and Australia. According to Walk Score, Vancouver, Montréal, and Toronto are the most walkable cities in Canada in 2020. New York tops the US list for 2020 at an overall 88.3 out of 100 followed by San Francisco.

Wearable devices with motion sensing technology are now used to monitor mobility-related activities. Wearable technology is defined as devices that can be worn or mated with human skin to continuously and closely monitor an individual's activities, without interrupting or limiting the user's motions (Haghi et al., 2017). Smartphones, smart watches, smart rings, smart bracelets, smart wristbands or headbands, and fitness trackers are examples of these wearable devices with motion sensing technology. Several walking apps provide the ability to offer walking directions; track users' walking workouts, all-day steps, or activities; and render their speed, traveled distance, and route. Examples of these apps include RideScout, Walkmeter Walking & Hiking GPS, MotionX-GPS, Virtual Walk, MapMyWalk, Argus, Fitbit app MobileTrack, Endomondo, and Charity Miles. WALKscope is also a crowdsourcing tool used by Denver residents to gather data related to walkability such as street information—sidewalk conditions, intersections, and pedestrian counts.

In many cases, for distances up to 10 km in urban areas, cycling can be the fastest of all modes from door to door (MMM Group, 2016). Innovative bicycle-related technologies improve cycling experience. These technologies include motion sensing, performance monitoring, seat detection, fitness planning, trip planning, and so on. Smart bikes are equipped with sensors that can continuously collect physiological and performance data such as speed, power output, pedal pressure, frame behavior, heart rate, temperature, humidity, and more. Smart bike helmets are equipped with built-in taillight, speakers, microphone, and Bluetooth connectivity. Strava, Zwift, Komoot, Cyclemeter GPS, ViewRanger, Map My Ride GPS Cycling & Route Tracker, Bikemap, and Google Maps are examples of mobile apps that help cyclists get the most out of their time on two wheels. Skin temperature in addition to glucose, lactate, sodium, and potassium in sweat or electrodermal activity (EDA) or a Galvanic Skin Response (GSR)–based sensor can be used to detect sweating. Special clothes can monitor a cyclist's hydration using bioelectrical impedance vector analysis (BIVA)–based hydration sensors.

Many cities around the world promote active mobility through several programs. For example, Brussels Mobility has launched a poster campaign #BlijvenTrappen ("keep pedaling") and temporarily offered free use of shared bicycles from the city's Villo scheme, resulting in 7,000 new subscribers. According to the Copenhagenize Index, Copenhagen is ranked as the 2019 most bike-friendly city in the world. The Copenhagenize Index is a comprehensive and holistic ranking of the world's most bicycle-friendly cities. Sixty-two percent of Copenhageners' trips to work or school are by bike, and the government invested more than $45 per capita in bicycle infrastructure (Colville-Andersen, 2015). However, according to the Bicycle Cities Index 2019, the Dutch city of Utrecht is the world's most bicycle-friendly city. North American cities are absent from the top ten with Montreal as the highest-ranked Canadian city (16th in the world) and San Francisco as the highest-ranked US city (39th in the world).

The LAirA (Landside Airport Accessibility)[9] EU-funded project focuses on multimodal, smart, and low-carbon airport access. This project encourages active mobility (walking, cycling, etc.) as an option for airports. The health economic assessment tool (HEAT) for walking and cycling is described in Kahlmeier et al. (2017) as a user-friendly yet robust evidence-based decision-making tool for transport and urban planners allowing the inclusion of physical activity benefits in transport appraisals. Urbano is another tool to promote active mobility in urban design (Dogan et al., 2020). This tool introduces two new urban design metrics called Streetscore and Amenityscore beside an expanded version of the well-known Walkscore.

4.7. Inclusive Mobility

The World Health Organization (WHO) estimates that 1.1 billion people (14.1% of the world's population) suffer from some form of disability. This represents the world's largest minority and the only minority group that any of us can become a member of at any time. An estimated 466 million people worldwide have disabling hearing loss, and this number is expected to rise to 1 in 4 by 2050. Globally, the number of people of all ages visually impaired is

[9] www.interreg-central.eu/Content.Node/LAirA.html

estimated to be 285 million, of whom 39 million are blind. Seventy-five million people need a wheelchair on a daily basis. This represents almost 1% of the world's population. About 200 million people have an intellectual disability (IQ below 75). This represents more than 2.5% of the world's population. According to the US Centers for Disease Control and Prevention (CDC), 61 million adults in the United States, more than 1 in 4 US adults (and about 2 in 5 adults aged 65 years and older), live with a disability (Centers for Disease Control and Prevention and others, 2019). Moreover, most people are likely to experience a mobility impairment at some point during their life (Davidson and Viita, 2020). The Open Doors Organization claims that more than 60% of people with disabilities in the United States report major obstacles when they travel. Population aging is also an increasing phenomenon due to declining fertility rates and rising life expectancy. For example, more than 35% of the population of a country like Italy will be over the age of 85 by 2050 (Tapus et al., 2007). As people age, transportation options often become more limited (Davidson and Viita, 2020).

Inclusive mobility aims at facilitating the mobility of frail seniors and physically challenged individuals. This matches with the concept of "Complete Trip"[10] defined by the US Department of Transportation (USDOT). Complete Trip refers to the seamless journey from a traveler's origin to destination, regardless of the number of modes, transfers, or connections. The success of a complete trip can be defined in terms of an individual's ability to go from origin to destination reliably, spontaneously, confidently, independently, safely, and efficiently without gaps in the travel chain regardless of location, income, or disability. Several governmental and nongovernmental organizations are paying attention to inclusive mobility and work on policy-related aspects and legislation. For example, the USDOT's Accessible Transportation Technologies Research Initiative (ATTRI) is leading efforts to develop and implement transformative applications to improve mobility options for all travelers, particularly those with disabilities (Martin et al., 2020). Under ATTRI, the USDOT has identified four application areas of interest that are common gaps in the Complete Trip travel chain. These four areas are Smart Wayfinding and Navigation Systems, Pre-trip Concierge and Virtualization, Robotics and Automation, and Safe Intersection Crossing. In January 2021, the US Department of Transportation announces over $41 million in awards for innovative technologies to improve transportation mobility and access for persons with disabilities through the "Complete Trip" program. The European Union funds several projects to support inclusive mobility. For example, the INCLUSION project[11] aims at understanding, assessing, and evaluating the accessibility and inclusiveness of transport solutions in European prioritized areas. This project identifies gaps and unmet needs and proposes and

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[10] www.its.dot.gov/its4us/index.htm
[11] http://h2020-inclusion.eu/

experiments with a range of innovative and transferable solutions, including ICT-enabled elements, ensuring accessible, inclusive, and equitable conditions for all and especially vulnerable user categories. The Canadian Disability Policy Alliance is a national collaboration of disability researchers, advocates, and policy makers, aimed at creating and mobilizing knowledge to enhance disability policy in Canada. One of these policies is related to mobility aids (specifically wheelchairs and scooters) for elderly and physically challenged individuals (McColl et al., 2015). The concept "barrier-free mobility" is highlighted in (Davidson and Viita, 2020) as a framework to guarantee accessible and independent mobility to all users including elderly and physical challenged individuals.

The technical components of inclusive mobility systems should be explicitly conceived and designed as part of a "socio-technical" system that models both the human and machine domains within a single conceptual framework, following a user-driven approach instead of traditionally used technology-push and problem-focused approaches. Without a user-driven research approach, there is a danger that ill-conceived technologies will at best be irrelevant or inappropriate and at worst will reinforce some of the negative ageist assumptions that frame much of society's response to aging and/or disability. This user-driven approach (Figure 4-3) can drive the specification, development, and deployment of the inclusive mobility system/platform in order to develop a mobility platform that will have practical benefits for users in their everyday lives.

The Disability Equality Index (DEI)[12] developed by Disability:IN is a comprehensive benchmarking tool that can help OEMs and mobility service providers build a road map of measurable, tangible actions that they can take to achieve disability inclusion. The Inclusive Mobility[13] program initiated by Volkswagen aims at directly engaging disability groups in the early stages of designing vehicle technologies and mobility services. Mobility aids for frail seniors and physically challenged individuals include, but are not limited to, wheelchairs and Personal Intelligent City Accessible Vehicles (PICAVs), smart laser shoes, GPS insoles and exoskeleton, or soft exosuits used in walking assistance. PICAV is an electrically powered one-person vehicle with specifically designed features for mobility-restricted people such as elderly and disabled people (Cepolina et al., 2011). Toyota's e-Palette is an electric AV designed to accommodate up to four wheelchair-bound passengers with additional riders. May Mobility also develops low-speed, electric, wheelchair-accessible automated driving vehicles. Voyage is deploying automated driving shuttle services at The Villages, the largest retirement community in the world. At Haneda Airport in Tokyo, people with disabilities will be able to hail autonomous wheelchairs using a smartphone app that lets them select a

[12]https://disabilityin.org/what-we-do/disability-equality-index/
[13]www.inclusivemobility.com/

destination, sit back, and relax (Scudellari, 2017). Alinker is a walk assist bike designed for people who have an illness or condition that impacts their mobility. Similarly Ford GoBike is designed for people with disabilities. Moreover, mobility service providers started to pay more attention to healthcare transportation services. Healthcare transportation refers to any transportation to medical facilities that is non-emergency in nature (e.g., to medical appointments, to an urgent care facility, or being discharged from the hospital) (Wolfe and McDonald, 2020). Several non-emergency healthcare HIPAA-compliant transportation services are nowadays provided to individuals with mobility- or financially related barriers. Examples of these services include Uber Health, Blue Cross and Blue Shield and Lyft, Cigna-HealthSpring and Lyft, and RIDE paratransit services.

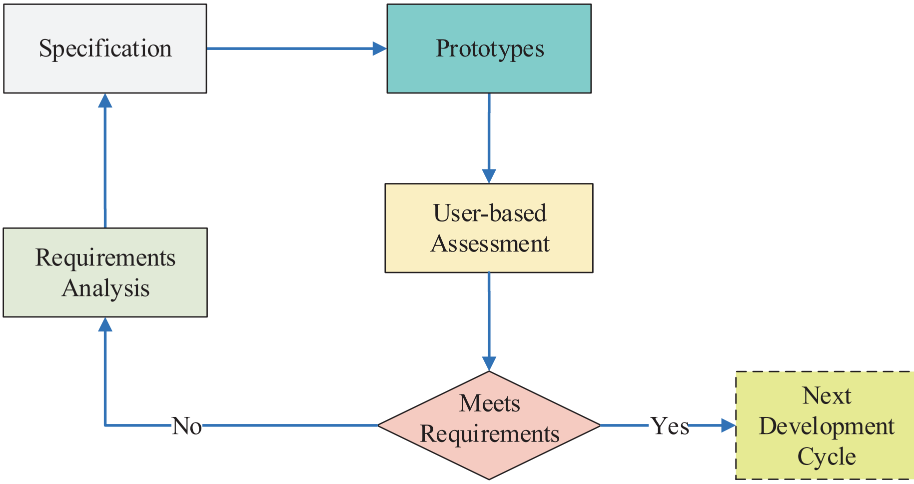

Figure 4-3. User-Driven Iterative Approach to Inclusive Mobility

Exoskeletons are the new wheelchairs that can reproduce the movements of walking as a way to compensate for the loss of mobility among the elderly and people with mobility impairment. ReWalk is a well-known wearable robotic exoskeleton that provides powered hip and knee motion to enable individuals with spinal cord injury (SCI) to stand upright, walk, turn, and climb and descend stairs. The ReStore exosuit is a lightweight soft exosuit that provides assistive torques to the wearer at the ankle and hip during walking. AI-based self-controlled legs were developed at the University of Waterloo to support the movements of the elderly and those with physical disabilities (Laschowski et al., 2020). Jaguar Land Rover unveils the shape-shifting "seat of the future" that tackles the health risks of sitting down for too long by making your brain think that you are walking. This seat continually adjusts via a series of actuators in the foam to simulate the rhythm of walking. A new mobility aid named Path Finder helps people who have trouble walking—simply by being fitted to their shoes (Rutkin, 2014). These shoes are designed specifically for Parkinson's patients who suffer from freezing of gait—a disabling clinical phenomenon that prevents people from walking or causes them to walk with extremely short steps. The laser projects parallel lines onto the next 50 centimeters of the floor in front of the patient, and pressure sensors trigger vibrations when a foot hits the ground. These smart shoes can help elderly, ill, and disabled people walk without fear of falling over. GPS tracking shoe insoles are used to monitor the location and track people with Alzheimer's or dementia. SensFloor is a large-area capacitive sensor floor, installable beneath any kind of flooring to increase the opportunity for smart personal engagement and monitoring. Smart paint crosswalks and smart cane technologies also help the visually impaired safely navigate crosswalks. The paint developed by the Ohio State University uses rare-earth nanocrystals that can emit a unique light signature, which a sensor added to the tip of a smart cane that can activate and then read. Established by Mobileye co-founders, OrCam provides wearable devices such as OrCam MyEye that allows visually impaired people to understand text and identify objects through audio feedback, describing what they are unable to see. Last but not least, several software services and apps are nowadays available to support inclusive mobility such as accessibleGO, Wheelmap, AbleThrive, GoGo Grandparent, Be My Eyes, and BlindSquare. For example, accessibleGO is a full-service accessible travel platform providing search, reviews, and bookings of accessible hotels, cruises, transport, and destinations worldwide.

4.8. Context Awareness Systems (CAS)

In her description of a theoretical model of situation awareness, Endsley defined situation awareness as the perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future (Endsley, 1995). Perception provides an awareness of multiple situational elements (objects, events, people, systems, environmental factors) and their current states (locations, conditions, modes, actions). Comprehension produces an understanding of the overall meaning of the perceived elements—how they fit together as a whole, what kind of situation it is, and what it means in terms of one's mission goals. Projection produces an awareness of the likely evolution of the situation and its possible/probable future states and events. To achieve a complete situation awareness, the smart mobility platform/system collects static and dynamic contextual information from hard/soft sensors in order to identify situation entities and their relationships. The system subsequently performs a relational analysis of objects-events followed by intent estimation and consequence prediction. Adaptation actions can be performed in response to changes in the situation/environment characterized by contextual information.

Contextual information answers situation-related questions such as who, what, when, and where in order to characterize the working environment and the system's agents (mobility platforms such as connected vehicles, connected bikes, or connected shuttle buses/transit and human agents such as drivers, passengers, and connected pedestrians) in terms of location, identity, activity, time, and status. Contexts can be classified into explicit context and implicit context. Explicit context contains the context parameters that are directly observable. Examples of explicit contextual information include, but are not limited to, pedestrian status, car location, traffic light status, battery status of an electric vehicle, passenger requests of a shared vehicle, trip details, and communication channel quality of service (QoS) such as bandwidth, throughput, packet loss, latency, and jitter. Implicit context includes parameters that need to be inferred directly. Quality of experience (QoE or QoX) (Möller and Raake, 2014) is an example of an implicit contextual information. Wu et al. defined QoE as "a multi-dimensional construct of perceptions and behaviors of a user, which represents her or his emotional, cognitive and behavioral responses, both subjective and objective, while using a system" (Wu et al., 2011). It is "the degree of delight or annoyance of the user of an application or service resulting from the fulfillment of his or her expectations with respect to the utility and/or enjoyment of the application or service in the light of the user's personality and current state" (Brunnström et al., 2013). This perception process is dependent on a triad of influential factors, namely, the vehicle being used and its specific features and conditions, the context in which it is being used, and the subjective (or human) personality and mental state of the user. Both driver's personality/preferences and their current physical, emotional, or cognitive state need to be inferred to get this implicit contextual information.

Taking contextual information into consideration can help in envisioning new services like info mobility/geo-marketing or triggering promotion as part of loyalty programs based on the location or offering other vehicular cloud services. This contextual information can also help in adapting the connectivity aspects based on the availability of bandwidth or other QoS parameters. Example of this adaptation may include establishing ad hoc V2V communication relay in case of losing the communication with the infrastructure or if the infrastructure we want to reach is outside the communication range of the mobility platform.

Personal navigation systems (PNSs) (Adam et al., 2020) are an example of a context navigation system that exists in mobile phones and several navigation or SatNavs apps (e.g., Google Maps, Apple Maps, CoPilot Premium HD Europe, TomTom GO mobile app, and Waze) and vehicle/bike sharing apps such as BikeHub. Wayfinding vision integrates personal navigation systems and context awareness. It incorporates the user's personal preset preferences, the user's activity, the local environmental conditions (i.e., how busy an airport is or how busy a motorway is), and the context detection algorithm for GPS-based location information and visual odometry and/or odometry (Symonds et al., 2017). Wayfinding can be considered as a CAS that provides guidance to a user's specific check-in area and departure gate; automated alerts for those in the same travel space who match your criteria (i.e., friends, specific business-type users); navigation and directional guidance; automated arrival information and local guidance, that is, for transportation options and heartbeat checks; and automated music according to a user's mood. Several context-aware mobility projects involve the integration of location information into wireless applications. For example, General Motors OnStar connects with customers on and off the road and provides them with easy-access offers through its Marketplace service. GM Marketplace offers users the ability to receive special promotions along with local recommendations and directions, and options to order from local stores and pay remotely via in-vehicle touchscreen and mobile apps. In collaboration with Salesforce, General Motors OnStar piloted a project to provide drivers/passengers shopping, fuel, or dining offers and deals based on their locations. Merchants have the power to put offers directly into Salesforce and get analytics to see campaign results. Another example of a context-aware service is Traffic Jam Whopper piloted by Burger King in Mexico City. The Traffic Jam Whopper project uses real-time data to target hungry drivers along congested roads and highways for food delivery by couriers on motorcycles.

4.9. Summary

This chapter gave examples of smart mobility technology enablers built based on the foundational technologies explained in the previous chapter. For example, road telematics and connected mobility leverage the wireless communication infrastructure, mobile computing services, blockchain, and IoT services to create data-rich environments able to accommodate different smart mobility services. The same applies to automated mobility that is evolving, thanks to the advances in foundational technologies such as AI and robotics. The shift toward electrification provided the foundation for e-mobility and micromobility services as a way to achieve decarbonized mobility with net zero emissions. Active, soft, or zero-impact mobility is also gaining momentum as an enabler for sustainable mobility. Inclusive mobility is an enabler to improve the mobility and living conditions of frail seniors and physically challenged individuals. Context awareness endows the mobility systems with the ability to adapt according to different contextual information. Adaptation implies the ability to deal with perplexing situations and to respond quickly and successfully to new situations. Contextual adaption is a highly desirable feature in future mobility systems. Adaptation is also a main sign of intelligence according to the Triarchic Theory of Intelligence and the English theoretical physicist and cosmologist Stephen Hawking (1942–2018) who saw intelligence as the ability to adapt to change. In the next chapter, we describe in detail a number of smart mobility disruptors developed, thanks to the availability of the technology enablers discussed in this chapter.

CHAPTER

5

Smart Mobility: Disruptors

"Disruptive innovation" is a term coined by Clayton Christensen, referring to a process in which an underrated product or service starts to become popular enough to replace, or displace, a conventional product or service. Disruptors are significantly altering the way consumers, industries, and businesses operate and can lead to game-changing products and services able to serve low-end or unserved consumers and migrate to the mainstream market. According to *The Innovator's Dilemma* (Christensen, 2013), disruptive innovation satisfies customer future needs and may provide lower performance in some key features but creates some unique features valued by the market. Expensive navigation systems and navigation features in Google/Apple Maps are examples of sustaining innovation and disruptive innovation, respectively. The former is more reliable and does not rely on network coverage but more expensive and does not provide real-time traffic updates compared to Google/Apple Maps. Mobility disruptors are usually not breakthrough innovations but significantly alter the way that mobility service providers operate, people move, and cargo is delivered. In this chapter, some disruptors in the area of smart mobility are highlighted.

A. Khamis, *Smart Mobility*, https://doi.org/10.1007/978-1-4842-7101-8_5

5.1. Kano Model

The Kano model (Figure 5-1) is an insightful way of understanding customers' needs for new products and services and framing innovations as a moving target. Disruptive innovation lies in the region between attractive quality and desired quality, while sustaining innovation is the region between desired quality and expected quality. As customer expectations change over time, attractive features become expected features. For example, car features such as power windows, power seats, adjustable steering wheel, and cruise control are moving from being desired features to being expected features. Other features like lane keeping assist, adaptive cruise control, blind spot detection, and prognostics are moving from being attractive features to being desired features, while features like automated valet parking and autonomous driving are still attractive features for many customers.

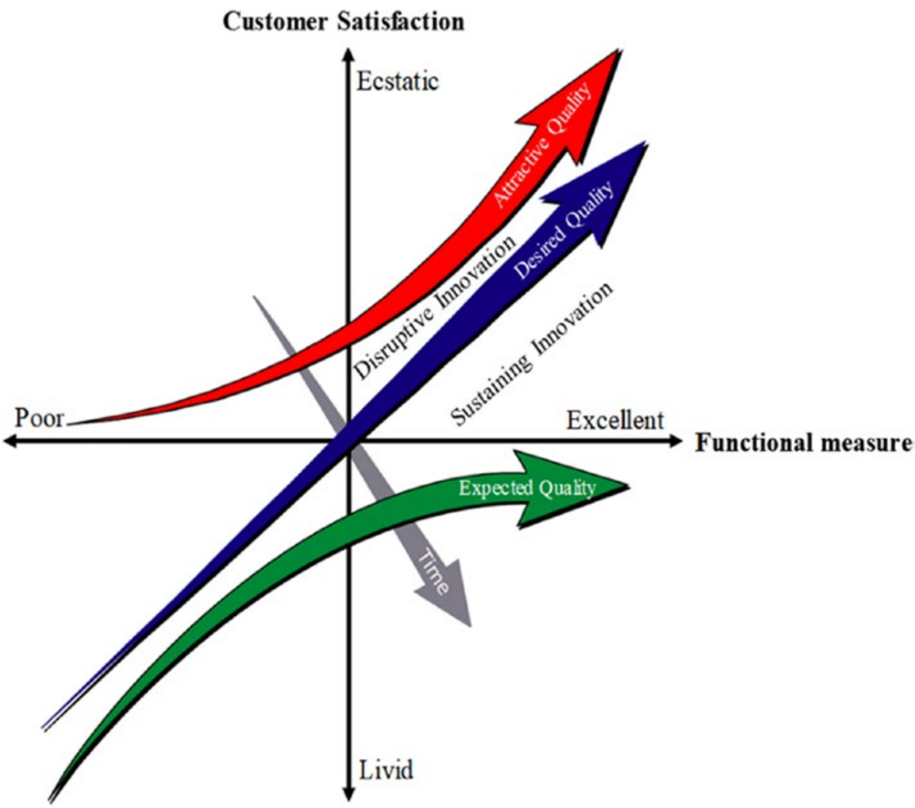

Figure 5-1. Kano Model

Customers may abandon the product/service and move to another product/service with more attractive features if the product/service does not reflect the evolving customer expectations. Many sustaining innovation–based companies went out of business such as Borders, Blockbuster, Kodak, and Columbia and have been replaced by software companies that adopted AI and disruptive innovation such as Amazon, Netflix, Flickr, and Apple Music. Now, Google is the largest marketing platform. Amazon is the largest bookseller, Skype is the fastest-growing telecom company, LinkedIn is the fastest-growing recruiting company, iTunes and Spotify are fastest-growing entertainment companies, and Airbnb is the world's biggest accommodation provider although it does not own any real estate. Moreover, Bitcoin is the world's biggest bank with no actual cash, Facebook is the world's most popular media owner that creates no content, Alibaba is the world's most valuable retailer with no inventory, and Uber is the world's largest taxi company with no vehicles.

Mobility disruptors include, but are not limited to, disruptive mobility platforms, shared mobility, Mobility-as-a-Service (MaaS), mobility on demand (MOD), seamless integrated mobility systems (SIMS), last-mile delivery, Vehicle-as-a-Service (VaaS), gig economy, and passenger economy. The following sections explain these disruptors in more detail.

5.2. Disruptive Mobility Platforms

Mobility platforms can be ground, aerial, or marine. The following subsections describe a number of disruptive mobility platforms that are emerging for people mobility and goods delivery.

5.2.1. Autonomous Ground Vehicles

Different concepts of autonomous ground vehicles are proposed, and some are tested to facilitate Mobility-as-a-Service (see Section 5.4), mobility on demand (see Section 5.5), and seamless integrated mobility (see Section 5.6) in cities, airports, malls, hospitals, and theme parks. Examples of these mobility concepts include self-driving shuttles (SDSs), smart carts, smart wheelchairs, and autonomous robot valets. Self-driving shuttles (SDSs) are vehicles that can navigate autonomously at low speed (less than 50 km/h). These vehicles provide an attractive, flexible shared mobility solution for first-/last-mile transportation and last-mile delivery. For example, the FABULOS project[1] focuses on how cities can use SDSs for last-mile transportation. Many OEMs are involved in the development of a variety of autonomous shuttle platforms. For example, GM's Cruise reveals its autonomous shuttle called Origin with no steering wheel or gas pedal for an upcoming ridehailing service. Origin is a connected, autonomous, and electric mobility platform that is meant to be a six-person taxi for ride shares in and around urban areas. This SDS is tested

[1] https://bit.ly/2KyYuX5

extensively on public roads in San Francisco. A fleet of the cars runs in a geo-fenced area of the city, operating a 24/7 ridehailing service that is strictly for Cruise employees so far as per the date of publishing this book. Table 5-1 summarizes potential applications, involved stakeholders, and expected social/environmental implications of autonomous shuttles.

Despite the aforementioned promising applications and benefits of autonomous shuttles, there are still some open questions to be answered before SDSs can widely spread and be used especially in public transit. These questions[2] include How open are riders to self-driving shuttles?, What are their concerns?, How will riders hail a driverless shuttle?, Will riders be able to hail shuttles without a smartphone and mobility provider app?, Where will the shuttle pick riders up?, Will some riders with disabilities need help getting into the driverless shuttles?, If they do, who will help them?, and Will riders be dissatisfied if a driverless vehicle takes them to a nearby bus stop instead of straight to their destination?

Table 5-1. Potential Application Scenarios of Autonomous Shuttles (Bucchiarone et al., 2020)

Use Case	Provided Services	Involved Stakeholders	Social/Environmental Implications
Autonomous shuttle as shared and integrated mobility	Shared mobility and multimodal mobility planning	Citizens, tourists, employees, and public companies	To incentivize sustainable mobility behavior, to optimize the planning, booking, and payment of multimodal public-private transportation
Tourism/info mobility/ geo-mobility	Tourist movement and targeted marketing advertising	Tourists, local governments, and commercial business owners	To improve the tourist experience and marketing traction to sponsors
Last-mile delivery of goods	Delivery of goods	Courier companies, commercial business owners, and citizens	Decongestion of city centers, reduction of operation/ delivery costs, air pollution reduction, and increasing customer satisfaction
Public/private surveillance management	Surveillance management	Citizens, tourists, employees, public companies, private companies, local police, and security companies	Real-time contextual data retrieval, monitoring activities, and coordination of responses in dangerous situations and detection of panic events

[2] www.wired.com/story/waymo-phoenix-partnership/

Another disruptive mobility platforms are the autonomous wheelchairs, the autonomous carts, and the autonomous robot valets. A smart wheelchair is presented by WHILL to address the significant inefficiencies of the current passengers with reduced mobility services in airports. WHILL NEXT can move autonomously after the passengers and can allow multiple units like luggage cart to travel in a single-file line. After unloading the luggage at the destination, the cart will automatically return to the next customer. An autonomous shopping cart called Eli can assist shoppers at supermarkets. It can navigate supermarkets, follow shoppers as they walk through aisles, avoid obstacles, and auto pay the collected goods. An autonomous robot valet named Stan can park your car at the airport. This robot has been tested at London's Gatwick Airport. Stan uses forklift-like arms and artificial intelligence to create up to 50% more space in a parking lot. Using the passenger's flight details, the Stan robot brings the car back to a cabin so it will be waiting for the passenger when they return.

5.2.2. 3D Mobility and Urban Air Mobility (UAM)

Trams/street cars/trains can be seen as 1-DOF (degree of freedom) mobility platforms as they rely mainly on the longitudinal motion and the freedom of lateral motion is quite restricted (except for the case of derailing). Cars have 2-DOF (lateral and longitudinal motion). 3D mobility is a paradigm shift from restricted mobility in two-dimensional streets to two-dimensional mobility space enabling 3-DOF mobility (lateral, longitudinal, and vertical motion) or more accurately 6-DOF mobility (lateral, longitudinal, vertical, roll, pitch, and yaw) considering the rotational movements. Within this paradigm, urban air mobility (UAM) refers to quickly evolving urban mobility systems for people and cargo transportation. Air taxis/flying taxis/flying cars are futuristic disruptive mobility platforms that are based on an on-demand aviation business model. They are piloted Vertical Takeoff and Landing (VTOL) aircrafts. These VTOLs are customizable to accommodate different numbers of passengers or for cargo transportation. eVTOLs utilize electric propulsion to fly in and around densely populated urban areas at speeds of up to 320 km/hr with approximately 200 miles of range. Examples include uberAIR, Uber Elevate acquired by Joby Aviation, JoeBen Bevirt's flying car, Airbus Flying Taxi, Maker's Archer Aviation, Boeing Flying Taxi, and Cadillac eVTOLs presented in CES 2021. Cadillac eVTOLs use a 90 kWh EV motor to power four rotors as well as air-to-air and air-to-ground communications and can meet customers on the roof and take them to the vertiport closest to their destination. Archer Aviation is partnering with automaker Stellantis for the manufacturing and with United Airlines for operations of its composite, eVTOL aircraft. This company plans to raise $3.8 B through its own Special-Purpose Acquisition Company (SPAC) merger. Production is set to kick off in 2023.

Important The global urban air mobility (UAM) market, which is expected to be valued at $895.0 million in 2023, would grow to $6,889.4 million by 2030, at a CAGR of 33.9% during the forecast period (2023–2030) according to Prescient & Strategic Intelligence.

The remotely piloted, four-seat eVTOL "City Airbus" with 15-minute autonomy from Airbus Helicopters has now been flown publicly for the first time in July 2020. Hyundai presented in CES 2020 a future concept of air mobility that consists of interconnected PAV (personal air vehicle), PBV (purpose-built vehicle), and a hub. PAV is an eVTOL vehicle that allows runway-free urban air travel. PBV is an eco-friendly urban and highly customizable vehicle for human or cargo transportation and can offer customized services in transit (i.e., coffee shop, medical clinic), and the hub is mainly the takeoff/landing point for PAVs and arrival/departure point for PBVs.

According to the NASA Urban Air Mobility report (Goyal, 2018), three challenging UAM use cases are envisioned:

- **Last-Mile Delivery**: Rapid delivery of packages (less than 5 lb. or 2 kg) from local distribution hubs to a dedicated receiving vessel. Deliveries are unscheduled and routed as online orders are placed.
- **Air Metro**: Resembles current public transit options such as subways and buses, with predetermined routes, regular schedules, and set stops in high-traffic areas throughout each city. Vehicles are autonomously operated and can accommodate two to five passengers at a time, with an average load of three passengers per trip.
- **Air Taxi**: The air taxi use case is a near-ubiquitous (or door-to-door) ridesharing operation that allows consumers to call VTOLs/eVTOLs to their desired pickup locations and specify drop-off destinations at rooftops throughout a given city. Rides are unscheduled and on demand like ridesharing applications today. Like the air metro case, vehicles are autonomously operated and can accommodate two to five passengers at a time, with an average load of one passenger per trip.

Several cities are experimenting with UAM focusing on air taxis (e.g., China's EHang,[3] Kitty Hawk in New Zealand,[4] and Dubai's drone taxi[5]) and air deliveries (e.g., Amazon Prime Air,[6] JD.com's drone delivery, China's Antwork drones for medical supply delivery during the COVID-19 pandemic, and US Zipline drones for medical supply and personal protective equipment delivery in the Unites States and in Africa).

The UK government is giving US $1.65 million to a startup to build a pop-up urban airport for "flying taxis" that will be opened later in 2021 in Coventry, England. This urban airport named "Air-One" will be the first eVTOL operational hub in the world.

Traffic management infrastructure, physical infrastructure for receiving packages or landing vehicles, and supporting technology infrastructure, such as automatic doors for admitting drones into warehouses, are identified by McKinsey[7] as critical infrastructure requirements for UAM.

There are still several challenges for the widespread and societal acceptance of UAM as last-mile delivery platforms, air metro, or air taxis. These challenges include, but are not limited to, safety of "Beyond Visual Line of Sight" (BVLOS) operations, safety in dense urban areas, privacy, noise pollution, visual disruption, wildlife impacts, dynamic geo-fencing, optimal routing and navigation especially in severe weather conditions, getting the package to the right person's flat, and compliance with airspace regulations. For example, BVLOS flights require certification and permission from aviation authorities in many jurisdictions around the world as discussed in Chapter 2. In January 2021, the FAA allowed for the first time fully automated commercial drone flights with BVLOS operations. The approval was given to American Robotics Inc. However, these drones are only allowed to fly along planned routes in rural areas with a limited altitude below 122 meters. Moreover, a human pilot is required to oversee each flight's takeoff remotely.

[3] www.ehang.com/ehangaav
[4] https://kittyhawk.aero/
[5] www.volocopter.com/en/
[6] www.amazon.com/Amazon-Prime-Air/
[7] https://mck.co/3bTYnk5

5.2.3. River Taxis

River taxis, water taxis, or water buses provide public or private transport mainly in urban environments. This urban water transportation has been used for hundreds of years in many waterway-rich cities around the world such as Venice, Bangkok, Tokyo, New York, Sydney, and Toronto to ensure rapid point-to-point transportation and reduce traffic congestion. Dubai Roads and Transport Authority (RTA) regulates several water transport modes such as water taxis (maximum of 10 passengers at a time), water buses (20 passengers), petrol abra/wooden vessel (20 passengers), hybrid abra (20 passengers) and electrical abra (9 passengers), and ferries (100 passengers). River taxis are being rapidly transformed by technology. For example, the water taxi THUNDER with hybrid propulsion is used to drive free of emissions in electric-only mode through the channels of Venice. These water taxis also drive in open waters to the airport where they can reach higher speeds with diesel engines so that the boat can recharge the batteries. SeaBubbles are an experimental hydrofoil e-water taxi that can reach a respectable top speed of 25 km/h, producing no wave, no noise, and no emission, and can be used as water taxis on demand in cities.

In the near future, autonomous boats will be used to ferry goods and people in coastal and riverside cities helping reducing traffic congestion on roadways and railways. For example, the Roboat project[8] seeks to develop a fleet of autonomous boats for transporting goods and people in the city of Amsterdam (Wang et al., 2019). Within the same project, MIT researchers designed 3D-printed, driverless boats that can provide transport and self-assemble into other floating structures.

Important According to MarketsandMarkets, the autonomous ship market is projected to reach US $14.2 billion by 2030, at a CAGR of 9.3% from 2020 to 2030.

Highly automated vessels are currently used in several countries especially in Nordic countries like Norway. For example, Ocean Space Drones 1 and 2 are two experimental autonomous boats built by the Norwegian company Kongsberg Maritime and are used by the Norwegian University of Science and

[8] http://roboat.org/

Technology (NTNU). Several other projects funded by the Norwegian government target to develop electric autonomous vessels to be part of new integrated transport systems, rather than replacing existing ships.

Changing maritime laws and regulations is still a challenge against accommodating the use of autonomous ships for people mobility and cargo delivery as discussed in Chapter 2.

5.2.4. Automated People Movers (APMs)

Automated people movers (APMs) represent sustainable and disruptive innovation of transportation systems that are fully automated/driverless, elevated, and advanced fixed guideway systems. APM uses electric drive bogies inside guideway tubes to propel suspended passenger cabins in different customizable sizes that vary from personal pods to multi-passenger pods at speeds that can exceed 160 km/h. Compared to Maglev and other types of monorail systems, suspended coach automated rapid transit requires much less infrastructure as shown in Table 5-2.

Table 5-2. Urban Maglev, Light Rail, Bus Rapid Transit (BRT) vs. APM | Source: Swift Tram

Factors	APM	Urban Maglev	Light Rail	Bus Rapid Transit (BRT)
Installation costs	$$	$$$	$$$$$	$$$
Right of way costs	$	$$$	$$$$$$	$$$$
Operational costs	$$	$$	$$$$$	$$$$
System capacity	Medium	Medium	High	Medium
Accessibility/frequency	High	Medium	Low	Medium
Available 247	Yes	No	No	No
Energy consumption	Very low	Medium	Medium	High
Travel speed	30 mph	55 mph	55 mph	55 mph
Dedicated cargo cartage	Yes	No	No	No
Weather affects ops	No	Maybe	Yes	Yes

5.2.5. Hyperloop and Urbanloop

Hyperloop is a disruptive transportation technology for people and goods. A hyperloop comprises a sealed vacuum tube with reduced pressure through which a floating pod/capsule travels with low air resistance or friction conveying people or goods at high speed (up to 1200 km/h). A hyperloop system combines the convenience of a train and the speed of an airplane. The SpaceX Hyperloop Pod Competition attracted attention from academia, industry, and governmental organizations to work on hyperloop technology. The objective of this competition is to design and build a subscale prototype transport vehicle in order to demonstrate technical feasibility of various aspects of the hyperloop concept. Key players include Hyperloop Transportation Technologies (HTT), Hyperloop One, AECOM, Hardt, and TransPod,[9] which introduced a hyperloop concept in the city of Toronto. So far, Virgin Hyperloop[10] has been the only company in the world that has successfully tested its technology at scale. The Virgin Hyperloop One concept represents a sustainable mobility scheme as it envisions the use of solar panels that cover the tube, makes better and less expensive use of the terrain compared to high-speed rail, and eliminates sources of mechanical noise, like wheels on a track.

Important According to Verified Market Research, the hyperloop technology market was valued at US $0.40 billion in 2019 and is projected to reach US $7.32 billion by 2027, growing at a CAGR of 47.14% from 2020 to 2027.

Elon Musk envisions the low energy cost of a hyperloop system compared to any currently existing mode of transport (Figure 5-2). NASA also suggests that a hyperloop will be five to six times more efficient than air (for short routes) and two to three times more efficient than rail (Taylor et al., 2016). However, there are limited details for the calculation of energy usage; therefore, these claims cannot be further interrogated (Walker, 2018). This is mainly due to the lack of real hyperloop systems or testbeds that can be used to carry out energy analysis for this emerging and disruptive mobility technology under different operating conditions.

[9] https://transpod.com/
[10] https://virginhyperloop.com/

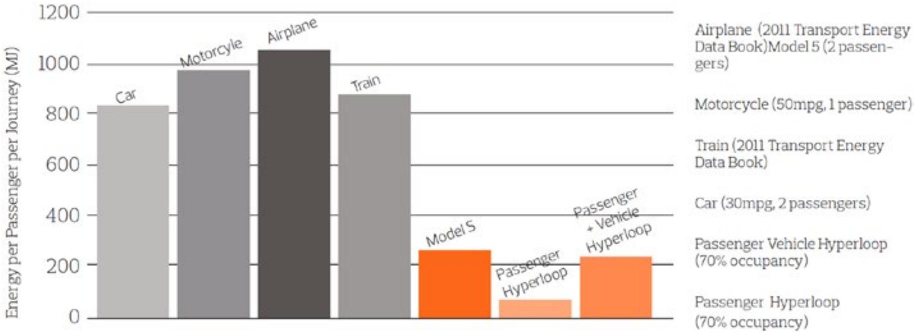

Figure 5-2. I Energy Cost per Passenger for a Journey Between Los Angeles and San Francisco for Various Modes of Transport (Musk, 2013)

Despite the fact that the hyperloop as an idea has been in the market for years now with interesting investment attractions, there is still a huge gap in the access to development and testing. To bridge this gap, I co-invented a multifunctional training and experimentation testbed for hyperloop (Khamis and AbdelFattah, 2019). This testbed[11] comprises a sealed tube with a vacuuming system, a capsule/pod levitated and propelled by an electromagnetic engine, a number of stations, a condition monitoring and control system, a HMI unit for local experimentation, a telepresence system for remote experimentation, an interactive virtual reality tool, and a digital twin. This testbed can be used for professional and educational training on hyperloop technology and other related technologies. It allows students, trainees, and researchers to study, experiment on, and understand the different aspects of hyperloop technology as disruptive transportation technology. The testbed enables different instructional and constructional activities showing not only how the hyperloop technology works but also what the technology can do.

The control system of this testbed controls the pressure level, schedules the operation of the capsules, starts the operation, and intervenes in case of emergency. The programming interfaces allow the execution of different control algorithms such as PID parameter tuning of the capsule, capsule localization using IMU or a reflective tape mounted within the tube or using hybrid localization (reflective tape with IMU-based localization), capsule dispatching, timetabling, and scheduling. Remote experimentation unit provides remote interaction with the hyperloop testbed for educational, training, and research purposes. This makes the testbed not restricted to synchronized attendance by instructors and students, enables constant access whenever needed by students, and also enables sharing resources with other institutions. The hyperloop digital

[11] www.youtube.com/watch?v=n5RzepPWwbU

twin is integrated in this testbed as a high-fidelity cloud-based virtual representation or a digital replica of the hyperloop that represents the different elements and the dynamics of the capsule. This digital twin incorporates 3D modeling, multiphysics simulation, and cognitive IoT capabilities to create a hyperloop shadow that contains an up-to-date and accurate copy of the hyperloop's properties and states throughout the entire life cycle of the system. The digital twin benefits include, but are not limited to, monitoring, diagnostics, and prognostics to guarantee the healthy, efficient, and sustainable operation of the system and optimize the operation and maintenance of the hyperloop testbed.

Another novel and disruptive form of ground transport is the urbanloop[12] that was introduced in France in 2018 as an urban mobility system for rapid travel. One- or two-person sports car–inspired transparent capsules travel in tubes that can be buried, semi-buried, or airborne depending on urban constraints.

5.3. Shared Mobility

In recent years, shared mobility technology has matured significantly—as is evident by the appearance of commercially available shared mobility services such as car sharing, bike sharing, scooter sharing, ridesharing, ridehailing/ridesourcing, and demand-responsive transit (DRT). Shared autonomous vehicles (SAVs) and pooled shared autonomous vehicles (PSAVs) are also quickly emerging. PSAVs are SAVs that serve multiple riders simultaneously.

Important The global shared mobility market size is projected to reach $619.51 billion by 2025, according to a report by Grand View Research, Inc., rising at a CAGR of 25.1% during the forecast period.

Different shared mobility services are provided based on a sharing and gig economy business model. These services represent a paradigm shift from ownership to usership. Shared mobility services include the following:

- **Vehicle Sharing Services**: Provided by companies like Zipcar, SHARE NOW, Getaround, Capital Bikeshare, Lime, VeoRide, and Bird, involve multiple customers operating the same vehicle at different times (Kimley-Horn et al., 2019).

[12] http://urbanloop.univ-lorraine.fr/

- **Peer-to-Peer (P2P) Vehicle Sharing Services**: Are emerging services offered by vehicle owners to other people in their area for short periods of time. This model is similar to Airbnb and Couchsurfing. In these systems, a mobility platform can be a car (e.g., Drive Drive Car), bike (e.g., Spinlister), scooter, Personal Intelligent City Accessible Vehicle (PICAV), VTOL, SeaBubble, or any other personal transporter.
- **Demand-Responsive Transit (DRT), Dial-a-Ride, or Paratransit**: DRT is a pre-booked, shared mobility service that combines both public and private transportation services to provide an experience similar to an on-demand mobility service. DRT is defined in (Bakker, 1999) as a transportation option that falls between a private vehicle and the conventional public transport, that is, a service that offers a similar level of service and mobility as private vehicles along with easy access to public transport. DRT provides dedicated small buses, minibuses, or maxi-taxis, which aim to cater pre-booked user requests through a telephone or a smartphone app (Talley and Anderson, 1986).
- **Microtransit**: The US Department of Transportation (USDOT) defines microtransit as "a privately owned and operated shared transportation system that can offer fixed routes and schedules as well as flexible routes and on-demand scheduling. The vehicles generally include vans and buses" (Kimley-Horn et al., 2019). Microtransit is a form of DRT. Examples of vendors or services for microtransit include Ford TransLoc, DemandTrans, and Transdev.
- **Ridesharing Services**: Provided by companies like Zimride, Getaround, and Waze Carpool, are a software-assisted modernization of conventional carpooling in which drivers with their own personal vehicles are matched with passengers using the same subscription service to split the cost of commuting together (Kimley-Horn et al., 2019). In ridesharing, the drivers fill seats in their car when they are already driving from point A to point B. This is not a new model as carpooling has been used for years since World War II when the US government encouraged people to carpool and share

rides as a way to conserve resources necessary for the war effort. The *"When you ride ALONE you ride with Hitler!"* US government propaganda poster was part of this unprecedented government campaign in 1943.

- **Ridehailing or Ridesourcing Services**: Provided by transportation network companies (TNCs) such as Uber, Lyft, and DiDi, consist of a driver utilizing their personal vehicle to provide a private trip to a paying passenger (Kimley-Horn et al., 2019). A driver is hailed on-demand to drive a passenger somewhere for profit.
- **Ridesplitting Service**: Offered by TNCs such as Uber and Lyft in major cities (UberPool and Lyft Line), is a close counterpart of both the ridesourcing and microtransit models as the drivers utilize their personal vehicles, drive professionally rather than as part of their own commute, and can accommodate multiple independent passengers simultaneously (as distinct from ridehailing that is oriented to an individual paying passenger) on routes that dynamically update in response to new trip requests (Kimley-Horn et al., 2019). Compared to microtransit, ridesplitting commonly uses lower-capacity vehicles (less than six passengers); and compared to ridehailing/ridesourcing, in ridesplitting, there is a higher likelihood of customers independently booking trips simultaneously, with start and end points that can be conveniently served using the same overall trip.

Another classification is provided by the Federal Highway Administration of the US Department of Transportation in (Shaheen et al., 2016). They categorize shared mobility into five groupings, namely, membership-based self-service models (e.g., bike sharing, car sharing, carpooling, vanpooling, and on-demand ridesharing), P2P self-service models (e.g., bike sharing and car sharing), non-membership self-service models (bike sharing, car rental, and casual carpooling), for-hire service models (e.g., courier network services of CBS, liveries/limousines, ridesourcing, or TNCs and taxis or e-hail), and mass transit systems (e.g., public transportation, micro- and alternative transit services including microtransit, paratransit, and shuttles).

A key advantage of shared mobility is its ability to fill gaps where traditional public transport is absent, inadequate, or ineffective (Kimley-Horn et al., 2019) especially in the countries with low Rapid Transit to Resident Ratio (RTR). RTR measures how many kilometers of mass transit exist in a country per million urban residents.

The United States has a RTR of 8.9, while France has a RTR of 30.2 (Hook and Hughes, 2017). Shared mobility is also an enabler for equitable transportation. Equitable transportation systems address the needs of previously underserved populations, enabling these groups to conveniently and affordably access destinations and opportunities.

Equitable transportation also means that system benefits (and externalities) are distributed equitably (Yanocha and Allan, 2019).

The COVID-19 pandemic has severely impacted shared mobility services as it raised people's concerns about possible infection. The impacts of COVID-19 on shared mobility are discussed in the next chapter.

5.4. Mobility-as-a-Service (MaaS)

At its core, servitization refers to industries using their "products" to sell "outcomes as a service" rather than a one-off sale (Vandermerwe and Rada, 1988). This means that the product is used as a platform to deliver and sell services. In the mobility domain, servitization enables delivering mobility as a service, rather than customers buying vehicles. Mobility-as-a-Service (MaaS) is described in Goodall et al. (2017) as Netflix's business model applied to urban transportation.

The current sharp separation between car, bike, train, and bus constitutes an obstacle to a seamless mobility. MaaS is the neo-liberalization of mobility systems that enables seamless mobility. MaaS America defines MaaS as "the delivery, through an integrated digital platform and across all available modes of transport, of seamless, infinitely adaptable, personal mobility services."[13]

MaaS involves integrating seamless payment and relevant infrastructure elements (e.g., parking and vehicle charging) to provide an attractive value proposition to customers using creative pricing and mobility packages (Kimley-Horn et al., 2019). Through MaaS, seamless integration between different mobility services can be achieved, mobility platforms will be more customer-focused, route planning will be easier, and simplified payment methods for users will be enabled. MaaS gives these individuals the ability to purchase access rights to an interoperable package of mobility services (car, taxi, bus, rail, bike share, etc.) owned by others, usually governments, mobility providers, and other individuals. This is facilitated by integrated aggregation and payment platforms, with intensive processing of big data to match provision to demand in real time (Thakuriah et al., 2017). Table 5-3 shows the seven levels of MaaS defined by MaaS America.

[13] www.maasamerica.org/

Table 5-3. MaaS Levels as per MaaS America

MaaS Level	Description	Services
0	Individual modes of transportation with digitized interface	Account-based systems and information available online
1	One-to-one integration between some private services	Joint offerings (e.g., tolling + car park, car + ferry, and car park and ride + bus services)
2	Integrated payment and ticketing across limited public and private modes of transportation services	Integration between private operators and public transport modes of operation
3	Unified interface for a single account used in multiple modes of transport services	A single meta-operator (private and public) through a traveler account
4	All modes are integrated, private and public, including routing, ticketing, and payment	Open data and standards are defined and commonly used by all transportation providers and MaaS meta-operators to provide services to travelers
5	Active AI choices based on travel preferences and near-real-time data for ad hoc changes to a journey	Based on traveler-specific behavior and profiling; minimal (to no) intervention is needed by the traveler for an end-to-end journey based on the traveler's preferences, past travel history, and filters
6	MaaS connects beyond mobility, interfacing with IoT, smart building, and smart cities	Convenient and seamless interface with the traveler's ecosystem

The evolving MaaS solutions expand shared mobility to a large scale, such as public transport, car sharing, car hire, cabs, and rent-a-bike. Vienna, Helsinki, and Hannover are examples of cities where MaaS solutions are already in use (Polle and Naper, 2021). MaaS depends on the availability of fully functioning digital platforms able to manage traveler journeys from beginning to end allowing the travelers to seamlessly "mix and match" different personal and shared mobility modes such as e-bikes, robo taxis, small urban commuters/ micro-commuters, autonomous shuttles, trains, planes, and other first- and last-mile transportation modes. This seamless mobility platform will help in increasing the availability, the affordability, the efficiency, and the sustainability of multimodal mobility systems. From the user perspective, MaaS is packaged as an app or another digital platform that provides services from public and private mobility providers. Users can pay for a trip using a mobility mode that fits their needs at a specific time and that takes them all the way to their desired destinations. These platforms should provide different mobile device–enabled services such multimodal mobility optimal and dynamic planning, one-click travel book-and-pay, dynamic pricing, rescheduling, real-time traffic and weather information, adaptive routing, smart parking, and so on. Mobile apps like Whim (Helsinki), UbiGo (Gothenburg), Qixxit (Germany), and Beeline (Singapore) are already allowing users to select and pay for a variety of transportation options. For example, the Whim app provides access to multimodal mobility services such as taxis, rental cars, public transport, and bike share. This app also learns users' preferences and syncs with their calendars to intelligently suggest ways to get to an event (Goodall et al., 2017).

Important According to MarketsandMarkets, the global Mobility-as-a-Service (MaaS) market size is projected to reach US $70.4 billion by 2030.

From the mobility service provider's perspective, the MaaS platform should endow the service provider with the ability to bundle services and easily share revenue. For example, the Siemens MaaS platform[14] enables bundling of mobility products for specific user groups and mobility needs. For instance, a professional bundle may include access to all public transport, 1000 minutes of premium parking, and 120 minutes of Limo service for 200 euros per month. A student bundle can include access to all public transport, unlimited bike sharing, and 2 days of car sharing for 80 euros per month. A family bundle may include a family access to all public transport, 500 minutes of city parking, 100 minutes of car sharing, and access to school buses for 130 euros a month.

An optimal or most popular combination of MaaS services can be recommended or customized based on user information and behaviors such as profession, region of living, daily commute, and bundle usage. For example, in downtown regions, people may want a package with 50% public transit, 35% electric bike or electric scooter, and 15% vehicle traveling time, while in the outskirts of a city, users may want more vehicle traveling time and less micromobility time. Brokering travel with suppliers, repackaging, and reselling it as a bundled package are other distinguishing characteristics of MaaS (Sochor et al., 2015). Several features of the Uber software platform such as journey planning and trip management are offered in several cities as Software-as-a-Service (SaaS) as part of the ridehailing company's broader strategy to push into public transit.[15] Moreover, Uber acquires Routematch[16] to make public transport more accessible. The evolution and mass adoption of MaaS by consumers is central to the emergence of passenger economy (Lanctot et al., 2017). The role of MaaS in passenger economy is highlighted in Section 5.9.

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[14]https://sie.ag/3qEOb2S
[15]https://bit.ly/2M757jF
[16]www.routematch.com/

One of the main challenges of MaaS is to find a right balance between the interests of the service providers and the passengers. The service providers aim to maximize their profit and usually prefer to allocate more resources to busier areas during high-demand periods, while passengers expect responsive and affordable services anywhere and at any time. Another main challenge in MaaS is developing efficient models of coordination and collaboration between mobility service providers. This coordination addresses the interdependency management among the cooperative or competitive mobility service providers in order to achieve their goals. According to a study conducted at the University of Texas at Austin (Pandey et al., 2019), having several mobility service providers competing against each other could worsen the quality of service of a MaaS platform compared to having a more centralized platform that creates a level of cooperation and generates the optimal assignment based on limited information from all service providers.

5.5. Mobility on Demand (MOD)

The US Department of Transportation defines mobility on demand (MOD) as an innovative transportation concept where consumers can access mobility, goods, and services on demand by dispatching or using shared mobility, courier services, aerial vehicles, and public transportation solutions and where passenger services such as trip planning and booking, real-time information, and fare payment are incorporated into a single user interface (Shaheen et al., 2017). MOD providers facilitate access to different mobility modes such as car sharing, bike sharing, scooter sharing, ridesharing, ridehailing/ridesourcing, transportation network companies (TNCs), micromobility, shuttle services, public transportation, and other emerging transportation solutions. Susan Shaheen and Adam Cohen highlight in (Shaheen and Cohen, 2020) the main differences between MOD and MaaS. MOD focuses on the commodification of passenger mobility and goods delivery and transportation system management, whereas MaaS primarily focuses on passenger mobility aggregation and subscription services. MOD is focused on providing a technology platform that allows customers to incorporate some level of on-demand option into their transit travel and potentially discover, book, and pay for modes using the same user interface (Kimley-Horn et al., 2019). A MOD system must be designed to respond to customer demands effectively (from the user's perspective) and economically (from the operator's perspective) (Mitchell et al., 2008). From user's perspective, trip time (the sum of pickup latency, transit latency, and drop-off latency) should be minimized, trip cost should be minimized, and trip convenience and experience should be maximized. From the operator's perspective, vehicle spatial distribution/allocation should be optimized (e.g., changing the vehicle distribution dynamically or vehicle self-organization in the case of autonomous vehicles in response to spatial and temporal distribution of the demand), a minimum number of vehicles should be deployed to serve a maximum number of customers, vehicle route should be optimized, and deadheading (miles driven with no passenger or payload) should be minimized, star rating should be maximized, and fraud/safety/dissemination acts should be avoided and prices should be strategically and dynamically determined to improve mobility node desirability. For example, studies show that dynamic pricing strategies of the operator impact the corresponding traveler choice behavior (Qiu et al., 2018). Dynamic pricing is widely studied in the revenue management literature (Talluri and Van Ryzin, 2006) and is an important problem now in the area of shared mobility and mobility on demand. Mitchell et al. illustrate in (Mitchell et al. 2008) the effect of dynamic pricing on node desirability. This study reveals that the costs to users and the system latencies are two key factors in the success of mobility-on-demand systems. System latencies in this context represent the times needed to walk from a trip origin to a nearby stack and pick up a vehicle, to travel to a stack near the desired destination, and to drop off a vehicle and walk to the actual destination. According to this study, the availability of high-quality trip planning facilitates sophisticated, dynamic pricing and the use of pricing to manage demand.

A TNC's surge pricing model is an example of a dynamic pricing model that raises the rates when traffic is heavy and demand for ridesharing is high. Some riders can choose to pay, while some will choose to wait a few minutes to see if the rates go back down. The Uber surge pricing model multiplies time, distance, and base fares during its busy hours (e.g., this multiplier can be 1.5x or 2x), while the Lyft Prime Time pricing model uses percentages to mark up its Prime Time pricing (e.g., if the rate is boosted by 50%, a fare that would normally be $20 costs $30).

5.6. Seamless Integrated Mobility Systems (SIMS)

The Canadian Urban Transit Association (CUTA) defines integrated urban mobility as "the ability for people to move easily from place to place according to their own needs." Deloitte defines seamless integrated mobility as building a convenient, well-connected, inclusive, and fast transportation system in the city (Wolff et al., 2020). According to McKinsey, seamless mobility could be cleaner, more convenient, and more efficient than the status quo, accommodating up to 30% more traffic while cutting travel time by 10% (Hannon et al., 2019). The World Economic Forum defines seamless integrated mobility systems (SIMS) as a "system of systems" that moves people and goods more efficiently by creating interoperability across physical assets, digital technologies, and governance rules. As illustrated in Figure 5-3, physical assets include different transportation modes, infrastructure, and energy/fuel networks.

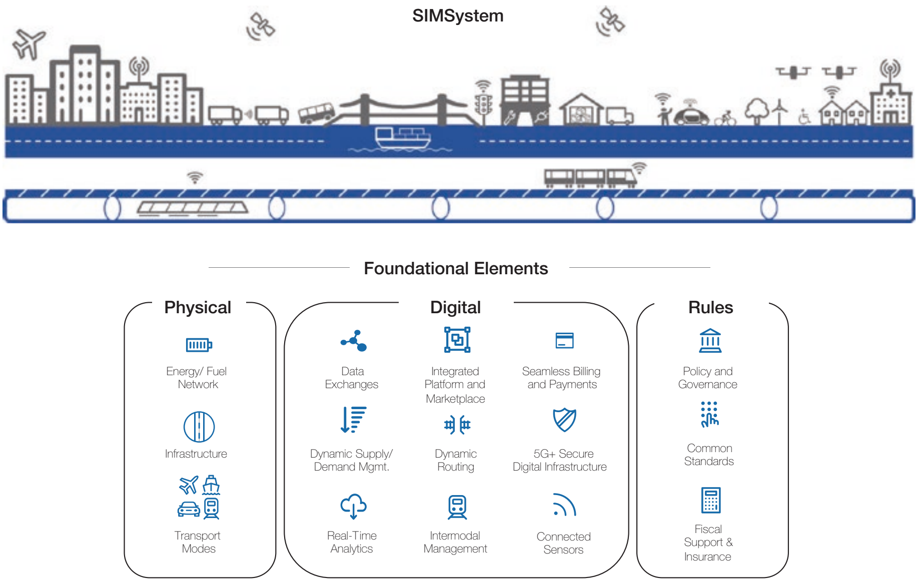

Figure 5-3. SIM System and Foundational Elements (World Economic Forum, 2018)

The digital platform represents the core of SIMS and provides a holistic, real-time picture of mobility supply and demand as well as the conditions of the overall system (e.g., traffic, infrastructure, weather). This digital platform enables different services such as dynamic pricing, seamless billing, shared data exchanges and dynamic routing, and intermodal management. Last but not least, the governance structures, standards, and rules cover the regulatory part of SIMS.

5.7. Last-Mile Delivery

Last mile is a term used in supply chain management and transportation planning to describe the movement of people and goods from a transportation hub to a destination (Goodman, 2005). Last-mile delivery is the last leg of transportation that focuses on the movement of goods from a warehouse or a distribution store to the final delivery destination, which is usually located around 11 miles or 17 kilometers from the warehouse. First-mile delivery addresses the movement of goods from manufacturer facilities to distribution hubs, while middle-mile delivery focuses on goods delivery from distribution hubs to warehouses.

Last-mile delivery is a process that has been around for as long as we have been doing delivery. However, customer expectations in terms of delivery speed, flexibility, and transparency are changing. These expectations have been pretty much set by Uber and Amazon alike. They dictated the rules of the game and its new standard. In order to meet customer expectations and comply with this new delivery standard, last-mile delivery systems should employ new technologies for faster, more elastic, and transparent delivery services. Last-mile delivery should use efficient digital platforms able to provide customers with the following:

- Flexibility of choosing a delivery service (couple of days delivery, next-day delivery, or same-day delivery or instant delivery with or without extra surcharge)
- Scheduling and rescheduling the delivery
- Selecting and changing pickup location (home/delivery to the doorstep, click and collect, parcel smart lockers, pickup and drop-off points known as PUDO points, curb-sides or dark stores, which are traditional retail stores converted into local fulfillment centers to eliminate disruption to in-store customers or deal with customers during pandemics)
- Visibility and transparency (delay notification, communication channel with dispatchers, and/or deliveries) regarding the nature of the delivery item in order to get the customer engaged and be part of the experience

Other services can be added for suppliers such as dynamic order orchestration, delivery tour planning, optimal deployment and efficient and adaptive routing, and fleet management.

Important As a share of the total cost of shipping, last-mile delivery costs are substantial—comprising 53% overall according to Business Insider Intelligence. According to McKinsey & Company, semi- and fully autonomous last-mile delivery systems will reduce costs by approximately 10–40% (Joerss et al., 2016).

Nowadays various innovative solutions for last-mile delivery are currently being developed or tested to reduce the delivery cost, increase customer satisfaction, and minimize the negative environmental impact. These solutions include, but are not limited to, cargo bikes, delivery to car (e.g., Amazon in partnership with General Motors and Volvo), self-service smart parcel lockers (e.g., Amazon, Quadient, RTN), and delivery inside home when the customer is away (e.g., Waitrose, Albert Heijn), e-Palette (e.g., Toyota e-Platte and GM BrightDrop EP1 and EV600), self-driving delivery droids, semi-/fully autonomous last-mile delivery trucks or delivery robots (e.g., FedEx's autonomous robot SameDay

Bot, Amazon Scout, Nuro, Starship, KiwiBot, and TeleRetail), delivery drones (e.g., Amazon Prime Air and 7-Eleven), and drones working simultaneously with trucks serving as their mother ships. For example, electrically assisted or electric cargo bikes or e-cargo bikes are very efficient environmentally friendly last-mile delivery vehicles. The power of these vehicles is usually below 250 W in order to remain in the regulatory category for electrically assisted vehicles (EAVs). The Civilized Cycles[17] e-bike can carry a rear passenger and is equipped with integrated locking hard-shell panniers around the rear wheel for carrying groceries, a laptop, and other daily work gear, or up to 50 lbs. of cargo. According to Velove Bikes,[18] these last-mile delivery electric cargo bikes can be up to 2x more productive and have a significantly lower total cost of ownership compared to van-based delivery.

The rapid increase of ecommerce during the COVID-19 pandemic was a catalyst for the surge in contactless last-mile services. The impacts of the pandemic on last-mile delivery are discussed in the next chapter.

5.8. Vehicle-as-a-Service (VaaS)

Aside from the previously discussed MaaS and MOD services, sensing and computational resources of modern vehicles can be offered as shared services. Nowadays, an average vehicle has 50 microcomputers, which are not fully utilized all the time. Modern vehicles are also equipped with different types of sensors in order to support assisted and automated driving functions. These sensors include, but are not limited to, cameras, LiDAR sensors, short-range and long-range radars, inertial measurement units, and/or vehicle dynamic data from the vehicle's CAN bus (vehicle speed, direction, brake status, turn signal status, etc.). These sensors can generate between 5 TB and 20 TB of data per day per vehicle depending on the level of autonomy (Twitter generates 12 TB of data per day). Even at a lower level of autonomy, around 5 TB can be generated per day per vehicle. Examples of vehicle data/information include

- **Vehicle Events**: Data that describes an event, notable state change, or anomaly within a vehicle
- **Customer Preference**: Data that describes a preferred setting within the vehicle
- **Customer Behavior**: Data that describes changes in conditions of the vehicle based on customer inputs

[17] https://civilizedcycles.com/
[18] www.velove.se/

- **Vehicle in Place**: Data that describes where a vehicle is in a three-dimensional space
- **Vehicle in Time**: Data that describes when a vehicle is in time
- **Vehicle Description**: Data that describes relatively static characteristics of the vehicle
- **Vehicle State**: Data that describes a set condition of a component, subsystem, or vehicle system

This vehicle data is seen as an asset that can be monetized following infonomics best practices. Infonomics is the theory, study, and discipline of asserting economic significance to information. It strives to apply both economic and asset management principles and practices to the valuation, handling, and deployment of information assets (Laney, 2017). Vehicle data and information can be shared with other nearby vehicles and/or infrastructure for enhanced safety and monetization opportunities. Infonomics provides the foundation and methods for quantifying data and information value and tactics for using and monetizing these data and information.

According to Frost & Sullivan, data monetization is expected to unravel ~33 billion in opportunity for OEMs, with the potential to monetize $100 per car across 140 unique use cases by 2025. However, according to a more updated survey conducted by McKinsey (Bertoncello et al., 2021), data monetization could deliver $250–400 billion in annual incremental value for players across the ecosystem in 2030. These players include vehicle-specific players (OEMs and dealerships), fleet operators, rentals, mobility service providers, telematics players, vehicle maintenance/workshops, and the extended ecosystem groups (e.g., governments, infrastructure players, charging and fueling providers, advertising and marketing, content providers, third-party market places, logistics and freight forwarding, financial services, and tech companies). On a per-vehicle level, connectivity could deliver up to $310 in revenue and $180 in cost savings per year, on average, in B2B and B2C settings by 2030. Nine clusters have been revealed in this report with 38 potential use cases for data monetization. However, OTA updates, R&D hardware optimization, and sales and service efficiency are the three use cases that are expected to deliver the greatest impact. For example, OTA updates can provide several revenue generation and cost-saving opportunities such as selling features throughout a vehicle's life cycle, post-purchase feature activation, reducing the number of variants OEMs need to create, and preventing or accelerating recalls. GM unveiled a new brain and digital nerve system called Vehicle Intelligence Platform (VIP) that will enable OTA software updates on all vehicles. This architecture supports 4.5 terabytes of data transfer per hour and is currently used in 2020 Cadillac CT5 and 2020 Corvette, and will be used on all GM models introduced over the next few years.

According to McKinsey (Bertoncello et al., 2021), most companies have been unsuccessful in monetizing data so far due to three main reasons. The first reason is failing to generate customer interest and differentiate their services. The second reason is not resetting the organization and not building capabilities that enable effective data monetization throughout the entire vehicle life cycle. The third reason is not establishing ecosystems for scaling.

Ontario's Autonomous Vehicle Innovation Network (AVIN) envisions several vehicular cloud services (Kadri et al., 2019). These services include Processing as a Service (PRaaS), Storage as a Service (STaaS), Network as a Service (NaaS), and Information as a Service (INaaS). PRaaS enables the utilization of the available on-board processing resources of connected vehicles. STaaS opens the door to use the available storage resources of connected vehicles as dynamic data centers or as mules or relays for data mobilization. NaaS enables the vehicle to serve as a mobile hot spot. Finally, through INaaS, a connected vehicle can be used as a resource for information for neighboring and remote entities such as other vehicles, infrastructure, smart homes, EV charging stations, and so on.

5.9. Gig Economy and Passenger Economy

Gig economy and passenger economy are two new business models that are facilitated by smart mobility systems and services. The following subsections introduce these models.

5.9.1. Gig Economy and Crowdsourcing

A gig economy is a business model in which short-term and flexible jobs are commonplace for independent contractors with different skill sets who are available for income-earning freelance activities without traditional, long-term employer-employee relationships. In most of the cases, these freelance activities do not require any previous work experience. According to an Intuit 2020 study on the future of gig employment, gig economy trends show that in the years to come, over 80% of major US-based companies would significantly increase their use of nontraditional jobs.

Gig economy in the mobility domain, especially in on-demand delivery, has gained remarkable moment in the last few years. Several first- and last-mile transportation services and last-mile delivery services are based on this gig economy. Examples include GoShare (assist customers in need of drivers or movers); Kanga, EZER, and Bellhops (for movers); Cabify, Amazon Flex, and Stuart (delivering parcels); Deliv (delivering parcels); FedEx Express (short- and long-distance delivery); and so on. A comprehensive overview of 24 gig economy–based apps is available here.[19] Most of these apps focus on enabling crowdsourced delivery and mainly same-day and instant delivery services based on the gig economy model due to the continuously growing demand for speedy delivery services.

Important According to management consultants at McKinsey & Company, the market for same-day and instant delivery will account for around 20% of standard parcel revenue by 2025 with expected average year-on-year growth of around 40%.

Examples of gig economy–based platforms for delivery services include Onfleet, OnTime 360, Bringoz, LogiNext, GSMtasks, eLogii, Dispatch Science, Track-POD, Locus, OptimoRoute, and Routific. Hailify is a logistics company aggregating ridesharing and delivery jobs for gig drivers into a single platform. Service partners benefit from having a broader driver pool, as well as using Hailify to provide insurance on a per-gig basis. Drivers benefit from having more jobs to choose from without needing to switch between services manually, which maximizes their earning potential over a time span.

There is still a debate about the sustainability of the gig economy model as a unique source of income for the independent contractors due to the low financial rewards of this model. The low financial reward is the result of the limited short-term work with limited stakeholders and the availability of a huge number of apps that offer similar services.

During the COVID-19 pandemic, demand for contactless last-mile delivery services was skyrocketing. This resulted in an increasing need for gig workforce to fulfill delivery tasks in a timely and cost-effective manner. The impacts of COVID-19 on last-mile delivery are discussed in the next chapter.

5.9.2. Passenger Economy

Passenger economy is a term coined by Intel to represent the economic and societal values that will be generated by fully automated vehicles (SAE level 5) (Lanctot et al., 2017). It is a new business model that aims at monetizing the user experience in driverless mobility platforms. This model requires reaching Connected Car Customer Experience (C^3X) levels 3–5 according to the McKinsey Connected Car Customer Experience (C^3X) framework. In level 3, preference-based personalization, all passengers will enjoy personalized controls and targeted contextual advertising. In level 4, multimodal live dialogue, all passengers will interact live with vehicles and receive proactive

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[19] www.appjobs.com/blog/get-a-delivery-jobs-like-amazon-flex

recommendations on services and functions. In the ultimate level 5, virtual chauffeur, all passengers' explicit and unstated needs will be fulfilled by cognitive AI that predicts and performs complex unprogrammed tasks (Bertoncello et al., 2018).

With Connected Car Customer Experience and automated driving, several consumer-centric products and services such as retail, health, finance, and media services can be offered to passengers. This passenger economy will be a US $7 trillion market by 2050 according to Intel.[20] For perspective, that amount is double Germany's gross domestic product (GDP) and four times Canada's GDP in 2021. According to Strategy Analytics, the largest revenue opportunity in the passenger economy lies in the use of MaaS offerings as consumers shift resources away from vehicle ownership (Lanctot et al., 2017). Consumers' use of MaaS offerings will account for nearly 55% of these revenues, or US $3.7 trillion.

Passenger economy can create several new opportunities to enhance and monetize the experience of passengers of connected, automated, and shared vehicles. In the future, fully functioning mobility systems will be developed to enable different subscription-based services to passengers related to education, leisure, business, and healthcare. An example of these smart mobility platforms is Toyota Boshoku's Tailored Space System (MOOX). MOOX is a combination of the words mobile and box denoting a private space that can be utilized freely while in motion. In general, automated driving vehicles can be repurposed for different opportunities aside from being a privately owned vehicle for personal use. These opportunities include mobile motels, Sleep-Cab, mobile beauty salons, restaurants, drive-away movies, mobile stores, mobile pharmacies, mini-clinics, and other brick-and-mortar businesses to name just a few.

5.10. Summary

This chapter gave examples of several mobility disruptors such as disruptive mobility modes, shared mobility, Mobility-as-a-Service (MaaS), mobility on demand (MOD), seamless integrated mobility systems (SIMS), last-mile delivery, Vehicle-as-a-Service (VaaS), gig economy, and passenger economy. Autonomous shuttle buses, urban air mobility and urban water transportation, automated people movers (APMs), hyperloop, and urbanloop are described in this chapter as examples of disruptive mobility platforms. Shared mobility and Mobility-as-a-Service (MaaS) are discussed as a paradigm shift from individuals' ownership of mobility vehicles to usership and servitization as the neo-liberalization of mobility systems. The main differences between MaaS, mobility on demand (MOD), and seamless integrated mobility systems (SIMS)

[20] https://intel.ly/3bYjNwr

are highlighted in this chapter. Advances in last-mile delivery services to meet customer expectations in terms of delivery speed, flexibility, and transparency are presented. Ideas to make use of sensing and computational resources of smart mobility platforms are described under the "Vehicle-as-a-Service (VaaS)" concept. Last, but literally not least, potential applications of these mobility platforms within gig and passenger economy spaces are presented.

The COVID-19 pandemic has several impacts on different smart mobility services. The next chapter discusses the impacts caused during the pandemic and provides insights about potential implications in the post-pandemic era.

CHAPTER 6

Smart Mobility During the COVID-19 Pandemic and in the Post-pandemic World

The outbreak of the novel coronavirus and its disease COVID-19 presented an unprecedented challenge for humanity. Globally, as of the first anniversary date of the COVID-19 pandemic, there have been more than 118 million

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confirmed cases of COVID-19, including almost 2.6 million deaths, reported to the World Health Organization (WHO) from 223 countries, areas, or territories. This accelerating pandemic changes all the aspects of our lives and will leave some scars in the post-pandemic world as well. It impacts the way we work, entertain, purchase, and interact with each other; the way governmental organizations provide services; the way education institutions teach and conduct research; and the way companies run, grow, and deal with a world continuously changing in unprecedented and unpredictable ways. Since characterizing COVID-19 as a pandemic in March 11, 2020, the WHO recommends several public health measures to deal with the pandemic such as social distancing, wearing masks, and finding, isolating, testing, and treating every case and tracing every contact. Governments around the world applied tight restrictions, curfews, and localized lockdowns as a way to curb the spread of the virus. Governments kept easing and tightening these measures causing serious changes in consumer behaviors and preferences and short-term disruptions and longer-term structural changes in different aspects of mobility systems as discussed in the following sections.

6.1. Smart Mobility During the COVID-19 Pandemic

The coronavirus outbreak caused widespread concern and economic hardship for mobility service providers. This pandemic affected all aspects of the mobility systems and services. Global sales of cars and trucks dramatically declined primarily due to economic uncertainty. Vehicle sales in the United States, Europe, and China dropped in April 2020 by 52%, 80%, and 3%, respectively, compared to April 2019 (Collie et al., 2021). In Canada, automotive sales fell by a staggering 74.6% in April 2020; and in the United Kingdom, sales fell by a seemingly impossible 97%—only 4,300 cars sold to private owners all month, countrywide (Stoddart, 2020). Moreover, several companies decided to get rid of some nonessential business to become more profitable as soon as possible. For example, Uber sold Jump, their bike share business, General Motors shut down Maven car sharing services and ARV e-bikes, and Ford and Lincoln canceled Rivian-powered electric vehicles. Public transit usership has also decreased due to mobility restrictions during the lockdown and the great shift to online learning, virtual meetings, and working from home as a new normal. Moreover, a safe physical distancing and sanity of the environment cannot be guaranteed in public transit. For example, the Toronto Transit Commission (TTC) in the city of Toronto dropped to less than 20% of its typical ridership since the province declared a state of emergency in mid-March (Boisvert, 2021). According to a survey conducted by the University of Toronto (Palm et al., 2020), 5% of respondents said they would return to transit during stage 1 of the province's three-stage reopening plan, while 63% said they would do so during stage 3. Statista shows that the pandemic has resulted in a significant drop in revenue for mobility services in Europe for 2020, as demand for flights, buses, trains, and ridesharing has plummeted considerably (Statista Research Department, 2021). Rental car giant Hertz formally filed for bankruptcy in May 2020 after its global revenue dropped by 73% in April 2020 from the same month in 2019. The pandemic also impacted the suppliers of the OEMs due to the production shutdown. For instance, Techniplas, a producer of plastic components for the auto industry, filed for bankruptcy in May 2020 citing the coronavirus, among other issues, as the reason for the filing. Most dramatically, several major airlines filed for bankruptcy or ceased operating or collapsed due to the coronavirus such as LATAM, Virgin Australia, Avianca, RavnAir, Air Italy, Jet Time, and AtlasGlobal.

Despite the aforementioned profound impacts of the COVID-19 pandemic on automotive sales, car rentals and public transit in urban mobility, shared mobility, and last-mile delivery services were notably impacted negatively in the case of shared mobility services and positively in the case of last-mile delivery services. The following subsections explain in detail how COVID-19 impacted these two sectors of smart mobility.

6.1.1. COVID-19 Impacts on Shared Mobility

To combat the coronavirus outbreak, governments all around the world applied strict lockdown measures that resulted in harsh reduction in people mobility and consequently drastic reduction in personal transportation (Hattrup-Silberberg et al., 2020). As people begin to abide by the social distancing and quarantine guidelines, shared mobility services like ridehailing/ridesourcing and carpooling become less attractive due to their susceptibility to coronavirus spread and less profitable due to the harsh reduction in people mobility especially during the lockdown and curfew periods.

According to a survey by McKinsey (Andersson et al., 2020), 45% of the respondents rank "reducing the risk of infection" the highest priority compared to only 14% before the pandemic. In contrast, the number of respondents who care most about "time to the destination" drops by 14%. The same survey also shows that only very few respondents think public transportation and shared mobility are safe. Another survey by CarGurus (Gurus, 2020) shows that almost 40% of Americans wanted to use taxis/rideshares less or not at all, while 49% said they would instead use their own vehicle more. In China, 66% of Chinese consumers indicated a preference for private vehicles for commute post the COVID-19 crisis, as compared to 34% before the crisis according to Second Measure's survey (Future Bridge, 2021).

During the pandemic, people spent 21% less in ridehailing services like Uber and Lyft, and Uber made 70% fewer trips in cities hit hard by the coronavirus (Future Bridge, 2021). According to Uber's financial report at the end of the second quarter of 2020, total revenue declined by 29% year-over-year, and mobility revenue declined by 67% year-over-year, which resulted in an 837-million-dollar loss, 28% more than last year (Uber, 2020). Despite this decrease in ridehailing services, shared micromobility services like bike sharing witnessed a relative increase in usage as these services provide open space with limited human contact.

Given the fact that most of the shared mobility services require people to share together a small and closed space that increases the chance of gathering together and contacting with others, this mode of transportation would increase the likelihood of both person-to-person transmission and surface-to-person transmission of the virus. Person-to-person transmission involves the inhalation of virus particles in enclosed environments, while surface-to-person transmission involves physical contact with a contaminated surface. This is why fewer users choose to use shared mobility services because of being afraid to get infected by strangers. In order to ensure passenger safety and guarantee the sanity of shared vehicles, ridehailing/ridesourcing/transportation network companies (TNCs) and shared mobility service providers are implementing very specific guidelines and strict public health measures. These measures include mandating that both drivers and passengers wear face masks, the use of protective shields, adding physical barriers between seats, controlling the number of passengers allowed in a shared ride or canceling the shared mobility services, the use of contact tracing, temperature scanning before use, providing drivers with disinfectant supplies, and thorough sanitization after each use. For example, DiDi is promoting the use of protective shields in cars (Future Bridge, 2021). Uber and Lyft have canceled the shared mobility services and only allow users to order vehicles for themselves. Moreover, several mobility players invested in new technologies geared toward guaranteeing the safety and sanity of the vehicles. Examples include antibacterial coating, antimicrobial surface protective shields, air filtration systems to prevent bacteria and other viruses from entering the car, air purification systems using nano-silver technology, and contact-free disinfection systems such as ultraviolet (UV)-C irradiation (200–280 nm). This UV-C can destroy vicious viruses without harming humans. Silicon dioxide–based nano-coating called "Liquid Guard" structured with sharp peaks and with a constant positive charge is used within the European project called "COVID Adapted Motosharing Services (CAMS)." CAMS explores the applicability of nanotechnology for physical removal of the novel coronavirus in SEAT motosharing services as a way to promote "virus-free" motosharing services. The coating is capable of attracting negative membranes, perforating and eliminating bacteria, fungi, spores, and viruses whose structure contains membranes. Liquid Guard has been tested for its effectiveness against *E. coli*, influenza A, and some forms of coronavirus including SARS-CoV-2. All of these measures increase the operating cost of the shared mobility services resulting in less profit compared to the pre-pandemic times.

6.1.2. COVID-19 Impacts on Last-Mile Delivery Services

The outbreak of COVID-19 has changed the shopping preference of the population and made them lean toward online shopping to minimize unnecessary contacts and to comply with mobility restrictions imposed during the pandemic. A survey of 1,000 Americans' shopping behavior during the COVID-19 pandemic showed that 87% were shopping online and 64% replaced traditional weekly shopping trips with online ordering according to TopData (Pastore, 2020). Another survey of 5,000 consumers from around the world conducted by Selligent indicates that 36% of consumers now shop online weekly, an increase from 28% before the pandemic (Selligent, 2020). According to Bazaarvoice's survey (Bazaarvoice, 2020), 62% of US shoppers say they shop more online now than they did before the pandemic. Globally, 49% of consumers shop online more now than they did pre-COVID-19. This change in shopping preferences and customer behaviors helped grocery and food service providers in continuing their business and surviving the lockdown from the pandemic and also encouraged delivery companies to test and deploy innovative delivery methods such as contactless delivery, curbsides or dark stores, unattended delivery, front porch delivery or leave at door delivery, and robot delivery. Some shared mobility service providers also started to focus on last-mile delivery services. According to Uber's financial report (Uber, 2020), the revenue of Uber Eats grew 103% year-over-year due to the pandemic.

The high contagiousness of the coronavirus results in one of the worst outbreaks. Social distancing is the main measure taken to reduce the spread of the virus through minimizing contact between people. Last-mile delivery robots played a crucial role in fighting the coronavirus spread as a contactless way to deliver medicine, food, or grocery. Contactless last-mile delivery systems and services can result in avoiding physical contact between caregivers and patients or between delivery workers and recipients. These contactless delivery systems benefit from the rapid proliferation of connected technologies and the recent advancements in semi- and fully autonomous delivery platforms that revolutionize the urban logistics and provide a safe and efficient delivery method for medical supplies (Niels et al., 2018), medications (Nianzhen, 2020), food, grocery, and other goods (Bangkok Post, 2020; Crowe, 2020).

The demand for food delivery has never been higher as most restaurants and cafés were closed during lockdown. The need for social distancing and surface disinfection has accelerated the development and adoption of robot delivery. Adopting robot delivery could eliminate the risk of person-to-person spread and by reducing human contact with the package reduce the risk of surface-to-person spread. Several delivery robots tested and deployed during the pandemic include Nuro driverless vehicle, Starship autonomous six-wheeled delivery robot, Unity Drive Innovation (UDI) self-driving vans, Dianomix Robox, Refraction AI REV-1 autonomous delivery robot, JD.com mini electric vans, Zipline drones, and Antwork delivery drones for medical supply deliveries during the outbreak.

The Nuro driverless vehicle has been approved for delivery tests in California in April 2020. This delivery robot uses its small fleet of road-legal delivery robots to transport pharmaceuticals to CVS customers in Houston, Texas. Customers who live in the service area can choose the autonomous delivery option when they are placing prescription orders via CVS.com or the CVS app. Nuro has a high security level as customers will need to confirm their identity to unlock their delivery when Nuro's autonomous vehicle arrives curbside at their home.

Starship robots can carry items within a four-mile (6 km) radius. Parcels, groceries, and food are directly delivered from stores, at the time that the customer requests via a mobile app. Once ordered, the robot's entire journey and location can be monitored on a smartphone. A UDI self-driving van uses LiDARs, cameras, and deep-learning algorithms to drive itself, carrying up to 1,000 kilograms on its cargo compartment, and is designed to deliver fresh fruits, vegetables, and other supplies. This unmanned vehicle provides a "contactless" alternative to regular deliveries, helping reduce the risk of person-to-person infection. Since the beginning of the pandemic, UDI has been operating a small fleet of vehicles in Zibo and two other cities, Suzhou and Shenzhen, where they deliver meal boxes to checkpoint workers and spray disinfectants near hospitals. Combined, the vans have made more than 2,500 autonomous trips from February to April 2020, often encountering busy traffic conditions despite the lockdown (Guizzo, 2020). Dianomix Robox is designed to drive on the sidewalk and deliver packages to one's porch. Refraction AI REV-1 is used to deliver food. This delivery robot can operate in the bike lane and on public roads and can reach a speed of 15 miles per hour with the ability to slow down in residential areas, obeying traffic lights and avoiding pedestrians, cyclists, curbs, trees, and light poles.

Zipline, a US-based drone delivery company, is delivering medical supplies and Personal Protective Equipment (PPE) in Ghana and Rwanda. Their drones can be launched five to seven minutes after an order is received, with flight times ranging from 15 to 30 minutes. These drones can also help collect COVID-19 tests and samples.

Hutchinson Health in Minnesota has been utilizing a relay delivery robot named "Jim" to deliver samples for COVID-19 testing, from the collection tent to the hospital lab without human contact, which greatly improved the turnaround time of testing. As a way to minimize the contact, a robot named

Rosé can bring almost anything to the guests' rooms, including wine, pillows, towels, groceries, and so on, at Hotel Trio in Healdsburg, California. The robot is sanitized after each delivery. Several other robots are used for the same purpose at Marriott and Hilton properties.

Several delivery companies have implemented new protocols for PPE and contactless delivery in order to mitigate potential risks of virus spread. These companies are investing heavily in disinfection materials and protective equipment for employees such as gloves and masks to reduce surface-to-person transmission. Several retail stores have been converted into local fulfillment centers or dark stores to serve the customers during the pandemic. To combat person-to-person transmission, Amazon has made available an "unattended delivery" option for customers, in addition to a "front porch delivery" option for scheduled delivery. Uber Eats similarly adopted a "leave at door" contactless delivery as an option for customers. However, finding the right pick-up and drop off points (e.g., main entrance or parking entrance or service gate), parking fines and delivering packages to a wrong person or a wrong address are common problems in last-mile delivery. According to Mapillary's Mapping in Logistics Report, over 95% drivers have faced problems with inaccurate mapping and over 71% drivers spend anywhere from 4 to 10+ minutes trying to find the exact drop-off location. In a city like New York, carriers typically pay millions of dollars in parking fines every year. For example, FedEx incurred 14.9 million in fines and UPS paid 33.8 million in 2018. Misdelivery and wrong delivery are frequently occurring problems in last-mile delivery services. The frequency of misdelivery or wrong delivery increases if the delivery worker handles multiple packages under time constraints, and these problems are more problematic in some last-mile delivery sectors such as medication and food delivery to multi-residential buildings.

This misdelivery problem results in customer dissatisfaction, negative brand image, and increased delivery cost for delivery service providers. According to the Office of Inspector General (OIG) Analysis of Postal Service Data (RARC, 2017), misdelivery is the first concern of all delivery customers (centralized delivery customers, small and medium-sized business or SMB customers, and customers aged 25–34). As a result of failed delivery, delivery service providers will have to refund the delivery charges to the customer, pay additional costs for redelivery, and sometimes offer the customer a discount as an apology for customer retention given the fact that 84% of customers who have a bad delivery experience would not buy from a retailer again (Magento, 2018).

Customer retention and margins were among retailers' top concerns at NRF, RILA, LINK, and Shoptalk in 2020. Yet most brands remain reactive when it comes to last-mile delivery, despite two key facts: 84% of customers who have a bad delivery experience would not buy from a retailer again, and last-mile transportation costs amount to 53% of the total cost of shipping. Brands must recognize delivery as a critical touch point, evaluating the levers available to impact growth and drive a healthy bottom line. In 2018, 13.5 billion retail packages were shipped in the United States. As many as 11.5% of the shipped packages suffered exceptions ranging from damages to bad addresses and simple weather delays. The cost of reshipping a single package can wipe out the margin of many other sales, simultaneously disappointing a customer who may never come back, exponentially increasing negative impact on the business. So many of these exceptions are addressable, and the negative repercussions are avoidable. Retailers that want to preserve margins and retain customers need to act on delivery issues before they impact shoppers.

An informed delivery platform is used to digitally notify users in advance of delivery of physical mail and allows users to report mail that was previewed in an email but does not arrive. However, this system is limited to the correct delivery and cannot handle the misdelivery cases. Inaccurate drop-off addresses, lack of high-definition maps, limited precision of publicly available and phone-enabled localization services used by delivery workers especially gig workers, and human mistakes of inexperienced delivery workers are the major root causes of misdeliveries.

6.2. Smart Mobility in the Post-pandemic World

With the new vaccine, life would get back slowly to a certain degree of normality prior to COVID-19 by the end of 2021, and markets are expected to recover by then. This pandemic was a great test of resilience of mobility companies and service providers. During the pandemic, major mobility players adopted defensive crisis management tactics to keep resilient through establishing dedicated safety protocols and applying strict austerity measures to conserve cash in order to keep employees and customers safe.

There is a lot of uncertainty around the mid-term and long-term impacts of the COVID-19 pandemic on mobility systems and services. Envisioning the post-pandemic world is very convoluted with multiple factors contributing to the success and failures of smart mobility technologies and business models. With the anticipated gradual return to normalcy, some speculations on smart mobility systems and services in the post-pandemic era are summarized in the following subsections.

6.2.1. Commuting Patterns

COVID-19 may change the commuting pattern permanently. Some employees are likely to continue to work from home as a new normal even after the pandemic subsides. According to a survey conducted by Statista (Statista

Research Department, 2021), almost two out of three employers state that some share of their workforce will remain permanently remote post-coronavirus. Several companies intend to allow their employees to work from home indefinitely (Paul, 2020). This will create an open opportunity for cities to better use the spaces (e.g., turning parking garage into green spaces and making the cities more walkable) and manage better the traffic. The pandemic showed the value of micromobility and soft/active mobility as a way to avoid spreading the virus. During the pandemic, many people replaced their daily pre-coronavirus commutes by what is called "pretend or fake commutes" such a walk around the block or cycling. In the post-pandemic world, the governments will likely invest more in making cycling and walking viable options. According to the Boston Consulting Group (BCG) (Bert et al., 2020), the United Kingdom announced a £2 billion package to put cycling and walking at the heart of Britain's post-COVID transportation plan—intended, in part, to protect the public transport network. Moreover, Milan relocated 35 kilometers of streets for bicycle and pedestrian use only.

6.2.2. Shared Mobility

In the post-pandemic world, demand for shared mobility might be recovering slowly (Future Bridge, 2021). People may be more reluctant to risk their health by using shared mobility and public transport. According to a Statista's survey (Statista Research Department, 2021), survey respondents in the United States overwhelmingly named their own car as the preferred choice of personal mobility during the pandemic and thereafter. However, the McKinsey Center for Future Mobility expects shared mobility solutions, including public transit, to rebound and continue to capture increased market share after the pandemic (Hausler et al., 2020).

6.2.3. Last-Mile Delivery

In the post-pandemic future, ecommerce will likely continue to grow but not at the same incredibly high rate observed during the pandemic. The increasing tendency toward online shopping and the permanent closure of several restaurants, theaters, and other attractions will also likely contribute to increased demand for last-mile delivery services. This behavior will be ever-lasting in the post-pandemic world. As more people experienced the convenience associated with online shopping and contactless last-mile delivery services during the pandemic, last-mile delivery will be more important than ever. This growing interest in last-mile delivery will accelerate innovation in this field making last-mile delivery services more capable of handling challenging aspects such as surge in ecommerce, health, safety, theft, failed deliveries, and misdeliveries.

6.2.4. Electric Vehicles

During the COVID-19 pandemic, the only segment of the car market that witnessed growing was electric vehicle sales. The pandemic caused a 20% drop in global light vehicle sales in 2020, to about 70 million. However, global sales of electric cars accelerated fast in 2020, rising by 43% to more than 3 million during the coronavirus pandemic according to ev-volumes.com. JP Morgan expects electric vehicle sales in China to grow by up to 30% as China's economy recovers from the effects of the pandemic. Cheaper batteries and longer-range vehicles, rather than government subsidies, are driving the growth according to JP Morgan analysts. The increasing societal interest in environmental issues will be another driver for electric vehicle market growth. COVID-19 has been a catalyst for interest in environmental issues and increased consumer interest in battery-electric vehicles. According to McKinsey's survey, more than 70% of survey respondents stated that delivery of goods should shift from vehicles with ICE to BEVs or H2EVs (also known as hydrogen fuel cell plug-in hybrid electric vehicles) for long-haul trucking and intracity transport and 40% of the respondents are even willing to pay a premium to enable this shift (Garibaldi et al., 2020).

6.2.5. Automated Driving Vehicles

In the post-pandemic era, transition to automated driving vehicles like robo taxis and delivery robots will likely accelerate as these vehicles support physical distancing in people mobility and contactless last-mile delivery. According to a recent McKinsey's survey, the number of North American respondents stating that they would be extremely or somewhat likely to take deliveries from autonomous vehicles increased from 18% to 28% (Garibaldi et al., 2020).

6.2.6. Work Strategy

In the post-pandemic world, mobility players will have to apply offensive tactics and may have to update their outdated operating strategies in the future for better agility as a way to face the expected recession and to reset the business.

6.2.7. Digital Transformation

After the COVID-19 pandemic, digital transformation is no longer an option, and every company will be very soon in one way or another a digital company. This will result in broad adoption of digital technology and digital innovation. For example, the COVID-19 pandemic has forced automakers worldwide to pivot and adapt the way they sell their vehicles at a fast pace. In order to achieve this objective, several players started to develop digital go-to-market (GTM) strategies and tools. Online shopping has become the go-to solution as a car-buying process in many places and as a way to replace the time-consuming showroom visits with a few minutes of online purchase. Beside Tesla, several other automakers and dealers launched online shopping platforms. Examples include GMC Shop-Click-Drive, Nissan@Home, and EZ Purchase Online. Tesla also plans to accept payments in cryptocurrency like Bitcoin. According to Google Think Auto 2020, 29% of car buyers would consider buying their next car online, and 40% of the Millennials are very certain about buying their next car online. Eighty-eight percent of Millennials reported that they had first discovered the vehicle they purchased "online." An auto financing survey conducted by McKinsey (Kempf et al., 2021) shows that online business–to–consumer sales for auto loans and leasing in the European market is expected to reach a market share of approximately 20–25% by 2025 reflecting the shift toward financing vehicles through digital channels. While these digital tools create opportunities to shop in new ways, the new norm in the post-pandemic era will be very likely a hybrid blending of online and store shopping.

6.2.8. Open Innovation

Innovation requires huge investment that is sometimes behind the capability of a single company due to austerity measures taken during the times of uncertainty. Companies are now more open to adopt open innovation policies through partnership. The McKinsey Center for Future Mobility (Heineke et al., 2021) shows that more than 420 partnerships in the area of self-driving vehicles, connected cars, electrified vehicles, and shared mobility have been concluded in 2020 compared to 110 in 2015. For example, Bosch came into collaboration with Microsoft in February 2021 to work on a software platform for vehicles. Toyota and Denso entered into a partnership with Aurora to design and build a fleet of autonomous taxis based on the Sienna minivan. Moreover, Cruise and GM announced in early 2021 a long-term, strategic relationship with Microsoft to further accelerate the commercialization of Cruise's all-electric, self-driving vehicles. The three companies will combine their expertise in software, hardware engineering, cloud computing capabilities, and manufacturing. In the post-pandemic era, companies will expand collaboration and partnership and will work together more frequently to build and expand innovative ecosystems.

6.2.9. Sustainable Development

This pandemic has shown us and the world leaders the urgent need to invest more in sustainable development. The pandemic may accelerate the transition toward sustainable mobility as world leaders start to pay more attention to sustainable development. The Great Reset initiative launched by the World Economic Forum (WEF) provides an opportunity to shape the recovery and to rebuild society and the economy in a more sustainable manner. One of the goals of the Great Reset initiative is to ensure that investments advance shared goals, such as equality and sustainability. This means that governmental recovery funds and investments from private entities and pension funds should be directed toward building "green" urban infrastructure and creating incentives for industries to improve their track record on environmental, social, and governance (ESG) metrics. This road map has the potential to amplify the mobility industry's focus on sustainability and increase e-mobility investment and sales in the post-pandemic era.

6.2.10. Global Solutions to Global Challenges

The COVID-19 pandemic played a decisive role in human evolution and created an unprecedented spirit of collaboration in the global science and technology communities and showed the need for open source knowledge, information, and data, resource sharing, and global solutions to the global challenges as a new norm in the post-pandemic world.

6.3. The Journey Is Far from Over

Like any other technology, smart mobility technologies have sunny sides and dark sides. Decreased crashes caused by human errors, reduced congestion and emission, improved efficiency, comfort, convenience, affordability and inclusivity, and increased economic advantage due to new business models like sharing economy, gig economy, and passenger economy are examples of the sunny sides of smart mobility. However, some dark sides of the smart mobility technologies need to be properly addressed to achieve the full potential of these technologies. Impacts on employment, privacy, and cybersecurity are among these concerns as explained in the following subsections.

6.3.1. Employment

Most of the tasks in people and cargo mobility systems can be classified as routine manual or routine cognitive tasks. People who are handling any 4D (dangerous, dull, dirty, and dumb) tasks will be negatively impacted by the smart technologies. However, smart mobility has the potential to create new businesses and innovate the existing ones resulting in higher productivity and better quality of services (Khamis et al., 2019). This will create a high demand for highly skilled workers such as algorithm developers, programmers, data analysts, machine learning specialists, robotics engineers, technologists, drone pilots, system engineers, market analysts, business developers, and marketing and services staff. However, these occupational categories necessitate people to upgrade their skills to be competitive enough and ready to handle these non-routine cognitive jobs. Smart mobility already opened doors to create new business models based on sharing economy that replaces ownership with mutual arrangements to boost incomes and, sometimes, create jobs. Digital shared mobility platforms, such as Uber and Lyft, are based on sharing economy business models that intensively use AI algorithms for vehicle deployment, routing, real-time tracking, dynamic pricing, and driver and rider ratings. Thanks to this model and this technology, several transportation network companies like Uber and Lyft managed to establish a functioning market for car hire services that is governed largely by supply and demand and creates millions of jobs. According to *MIT Technology Review* (Condliffe, 2017), the number of self-employed drivers shot up by 50% after Uber's arrival in each city it serves, but the number of regularly employed taxi drivers also had a small increase. Uber claims that its average New York City driver earns over $90,000 a year (Rogers, 2015). As explained in the previous chapter, several on-demand last-mile delivery services have been created based on the gig economy model. In order to provide services like same-day and instant delivery especially for food, grocery, and medication, delivery service providers have started to rely more on crowdsourced delivery through gig workforce to handle a big portion of the delivery tasks. The COVID-19 pandemic has highlighted the importance of this alternative workforce to deal with the sharp increase in online shopping. There is still a debate about the sustainability of the gig economy model as a unique source of income in the post-pandemic era. More formal studies about possible structural unemployment of smart mobility technologies and the alternative job opportunities these technologies create based on sharing and gig economy models are still required.

6.3.2. Privacy

Data is the food for the perception and automated decision-making algorithms that are used in smart mobility systems. Personal data needs to be collected by the service providers invisibly and passively and sometimes happens as a by-product of another service. We have almost lost our privacy tracked by web clients, Internet service providers, cell phone service providers, agents, and so on. We cannot decide who access our data, when they access it, and for what purpose. Sacrificing privacy is one of the dark sides of personal technologies. Some privacy questions are raised by Deloitte including Would the manufacturer of the vehicle own that data?, What about the person who bought, borrowed, or is simply a passenger in that vehicle?, How might our legal systems consistently define ownership?, What would happen when the vehicle crosses boundaries of jurisdiction?, How would a police agency handle logs from a connected vehicle involved in an accident?, and At the end of their lives, who would be responsible for wiping clean obsolete data recorders (Leon Nash and Hillaker, 2020)? These concerns apply to all connected, automated, and shared mobility technologies. As mentioned in Chapter 4, vehicle-to-grid (V2G) technology can help in improving EV affordability as it enables the EV owners to gain money through pushing the energy back from the battery of an electric car to the power grid. However, data privacy and cybersecurity are still challenges for V2G. Guaranteeing transparency (why should the data be shared?), trust (with whom will the data be shared?), and value (what are the benefits of sharing the data?) can help in the societal acceptance of V2G technology. The EU General Data Protection Regulation (GDPR) is developed to protect data and privacy in the European Union. The California Consumer Privacy Act (CCPA) is also another important step toward enhancing privacy rights and consumer protection for residents of California. However, more global measures and regulations should be developed to protect privacy and enforce digital rights. For example, a wide range of contact tracing, people tracking, and surveillance technologies have been applied during the pandemic in all aspects of our life, and mobility was not an exception. Measures have to be taken to protect digital rights, stop the surveillance once the pandemic is over, and ban new totalitarianism of surveillance technology and digital totalitarian states or digital Leninism.

6.3.3. Cybersecurity Attacks and Physical Attacks

NHTSA defines cybersecurity, within the context of road vehicles, as the protection of automotive electronic systems, communication networks, control algorithms, software, users, and underlying data from malicious attacks, damage, unauthorized access, or manipulation. The proliferation of technologies embedded in smart mobility systems opens the door to serious cyber threats and increases the potential of cyber-attacks. Ransomware infections, data breaches leading to the exfiltration of personally identifiable information, and unauthorized access to enterprise networks are among major self-driving vehicle cybersecurity concerns identified by the FBI. Deloitte highlighted two potential attacks in future mobility systems: hacking into manufacturer-to-vehicle communications and hijacking vehicle controls and sensors (Leon Nash and Hillaker, 2020). For example, attackers might conceivably have surreptitiously installed a surveillance device, leaving a transceiver to extract customer data or inject malicious data into the vehicle network, according to Deloitte. They can also steal sensitive vehicle data such as performance statistics or cryptographic keys. Hackers may also intend to gain control over safety-critical features such as steering, braking, propulsion, and OTA updates. Hackers can spoof traffic data to mess with traffic lights causing traffic jams and unnecessary rerouting. Michigan researchers were able to gain control of traffic lights to prove that an adversary can control traffic infrastructure to cause disruption, degrade safety, or gain an unfair advantage (Ghena et al., 2014). Cybersecurity vulnerabilities and mitigation efforts are summarized in Parkinson et al. (2017).

Other types of attacks may include robojacking, bullying behavior, or other unpredictable behaviors some people may show when they interact with smart mobility technologies. A pedestrian may seek to bully a self-driving zero-occupant vehicle (ZOV) through adversarial behavior or deceptive/cheating behavior such as showing rude gestures or stopping on the crosswalk in front of the vehicle for a long time. Other robojackers may try to vandalize the vehicle or steal high-value cargo from inside the vehicle. In a mixed traffic scenario, human drivers may show mischievous behavior and try to bully self-driving vehicles by driving erratically near them or zigzagging down the highway, weaving in and out of a self-driving platoon (Lipson and Kurman, 2016). Cheating on a mapping service or other GIS apps is another form of attack that can cause disturbance in the mobility systems. In February 2020, Simon Weckert managed to cheat on Google Maps' AI algorithm by creating fake traffic using a cart full of 99 phones with Google Maps' navigation turned on down the streets of Berlin creating massive traffic jam, even though there were zero cars on the road.

The United Nations Economic Commission for Europe (UNECE) developed regulations to improve automotive cybersecurity and software update management (United Nations, 2002). These regulations require automakers to implement measures to manage vehicle cybersecurity risks, secure vehicles by design to mitigate risks along the supply chain, and detect and respond to security incidents across the vehicle fleet and provide safe, secure software updates that do not compromise vehicle safety. Connected mobility stakeholders consider cybersecurity as a key to enable advanced communications and safety features. Robust authentication and authorization are provided to facilitate access to the vehicle using secured digital keys. Data encryption and anonymization are used to guarantee both the safety of the vehicle against cyber-attacks and the privacy of the occupants. Analysis of the data collected in an encrypted environment enables timely detection, recognition, and identification of malicious cyber-attacks that can lead to abnormal traffic signal behavior, vehicle tampering or intrusion, abnormal driving, and so on.

6.4. Summary

I hope to have convinced you that smart mobility is the promotion of sustainable mobility that guarantees seamless access to different modes of mobility and enables people or cargo to get from one place to another in a way that is safe, clean, and most efficient (fast, convenient, comfortable, productive, and cheap). There are two take-home messages of this book. The first message is that the future mobility is people-centric, software-defined, connected, and electric. The second main message emphasizes on the fact that the widespread and the societal acceptance of smart mobility technologies will depend not only on the maturity of the technology but also on the availability of a well-developed governance framework and proper city planning to accommodate these evolving technologies. Mobility technologies are getting smarter, and we need to be much smarter than we have been in the past to properly regulate, accommodate, and correctly use these emerging technologies.

B

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