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Danielle Attias *Editors*

The Robomobility Revolution of Urban Public Transport

A Social Sciences Perspective

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Foreword

It is because the future is made of uncertainties, that it deserves our interest, passionately and collectively. If the games were already played, what would be the point of moving heaven and earth to try to change the course of things? Acting on the present to prepare a future in which we want to live is the very essence of foresight, to which this book invites us. On the path we are going to take toward this future, we will all have the first step to take and to engage in a mobility transition; the scenario of inaction is no longer tenable.

Mobility is the breathing of the territory, and making it evolve means directly changing people's lives. Therefore, the question that arises with automated vehicles is whether they have the power to transform territories and lifestyles and access to the city's resources. This is the approach that the prospective workshop *La vie robomobile* is leading, since its foundation in 2017, by the Ministry of Ecological Transition, the Gustave Eiffel University, and the Laboratoire Aménagement Economie Territoires, to which Stratys has been actively contributing since its beginning.

It is up to society, individuals, and regional players to decide whether or not to take up technological innovations and to support the emergence of new models, particularly in the field of public transport and urban mobility. Just as the hegemony of the automobile can be problematic, it is not a question of switching to a new uniform and monolithic model in the future, where a single other mode would replace the solo car. For transport automation, several socio-technical models exist: the choice is possible, as long as we fully grasp the subject, experiment, test, keep our feet on the ground, and of course anticipate.

That's the whole point of an approach based on a bundle of solutions, which has its natural extension with Mobility as a Service. Autonomous shuttles fit in perfectly with this logic and are the translation into action of a public policy in favor of shared mobility and mobility as a vector of social ties and territorial cohesion. This is a sign of mobility where public authorities intend to play an active role in the regulation of a mobility market in the broadest sense, regardless of whether it is motorized or not, automated or not.

Many uncertainties remain regarding the economic model, such as the impacts on lifestyles, actual uses, the concrete scope of the technology, the ability to finance these changes, and the adequacy of the legal framework. However, instead of seeing them as constraints or obstacles, these uncertainties are equally grey areas in which everything or almost everything remains to be invented. This collective book will provide guidelines and tools to help you understand the potential for "game change" in the automation of public transport in the regions.

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Introduction: Bricks and Mortar of the Urban Public Transport Revolution

With more than a half of the world's population currently living in urban areas, mobility has become a key factor affecting citizens' well-being and life quality, as well as economic development. Policy makers are well aware of the mobility leveraging effect, and regulation is rapidly evolving.

Over the past two decades, society has been witnessing how technological, political, and societal changes have been transforming individual and collective urban mobility. Driven both by newcomers and traditional players, by disruptive as well as incremental innovations, by technology as well as uses, mobility offered today has become more diversified and more complex than ever.

This transformation has been mainly enabled by the widespread adoption of internet-connected devices (e.g., smartphones and tablets) and by innovative business models, technologies, and use-cases that arose from this rapid digitalization, such as peer-to-peer, and two-sided markets providing several mobility schemes: car-sharing, car-pooling, bike sharing, free-floating (cars, bikes, electric scooters, etc.), and ridesharing as well as ride hailing either for long distances and for urban micro-mobility.

The sum of these innovations has contributed to forge the concept of Mobility-as-a-Service (MaaS), which aims at offering customized transport services by uniting already existing transport solutions and transport providers, and offering them in a package to customers on a single subscription – and via a single interface of a service provider.

In that new landscape of MaaS, public transport acts as a backbone by linking all the other mobility offerings together in order to provide a seamless multimodal journey from point A to B for urban travelers. Thus, its stakeholders are leveraging a real paradigm shift accordingly with technological innovations, policy and regulation evolution, and travelers' behavioral changes. The collateral effect expected from this new globalized approach of mobility is the reduction of vehicle ownership, and its corollary congestion, road accidents, and pollution in cities.

Among these many innovations, public transport operators have been experiencing the arrival of Autonomous Vehicles for Collective Transport (AVCTs). At the current early stages, these vehicles are capable of autonomously carrying up to 15 passengers and are proposed to fulfill the first- and last-mile requirements as well as micro-transit services, aiming to transform the traditional fixed-route public transport into a customized on-demand offering. In the upcoming years, as shown by current experimentations, autonomous driving can be deployed by means of different types of AVCTs like regular-sized buses, five-seater cars, or even drones and helicopters. This transformation toward robomobility is a tangible revolution for urban public transport mobility.

Departing from the perspective of the social sciences, the book presents – in a holistic manner – how this revolution is happening; what are the major cornerstones for the implementation of robomobility; and, more largely, which levers are transforming urban mobility. It aims at answering several following substantial issues: *What is robomobility and what does it imply for the different stakeholders of the public transport ecosystem? How do policy makers integrate this innovation and how ready the regulations are? How do citizens take part in this transformation? What is the level of user acceptance for this new type of mobility? How to measure the economic impact of deploying autonomous collective vehicles in a local ecosystem? How decision-making processes are defining the public transport transformation?*

For now, the technology itself is no longer the major hindrance for autonomous fleet implementation, and their deployment speed is very much linked to their socio-economic impacts. Therefore, this was written from the viewpoint of the social sciences to prospect mobility challenges and forthcoming innovations. We aim to analyze to which extent innovation may prove beneficial or adverse in achieving common societal and economic goals by presenting a better understanding of mobility ecosystems and how their stakeholders perceive and value innovation's future use.

The book is written by a multidisciplinary and transnational team of academics – experts in the field of urban mobility – who work on three different levels: theoretical, tactical, and operational.

On the theoretical level, the book proposes a large review of research conducted on urban mobility by several scholars around the world for the last decade. The major stakes are taken into account and analyzed at their current stage as well as with a prospective view on politics, society, and technology.

The tactical dimension is tackled by in-depth analysis of mobility innovations and more specifically robomobility experimentations and the lessons to be learned concerning user behavior, governance, and integration in a global MaaS ecosystem.

Within an operational perspective, the book proposes two tools to evaluate and simulate the impact of robomobility: one tool is a decision support tool that helps to conduct an economic impact evaluation, and the other one is a methodology to assess the regulation openness for autonomous driving.

By combining these three levels: theoretical framework, real case studies, and analytical tools, the book brings relevant insights both from an academic and from an empirical standpoint.

The book is divided into two parts: the first part focuses on robomobility, and the second part broadens the viewpoint by placing robomobility into the larger range of urban mobility innovations.

Part I focuses on the different key points of robomobility implementation into public transport networks. Because robomobility may introduce remarkable changes in the way public transport meets their demand, its deployment represents the major challenge for public operators and policy makers as well as regulators. This part presents the big picture of autonomous public mobility and goes deeper into its three big challenges: policies, regulation, and economic impact. This part is concluded by the detailed presentation of a large experimentation on a European scale.

Part I comprises five chapters that are detailed hereafter.

In Chap. 1, Fabio Antonialli brings an overview of the evolution of automation in public transport, from the first automated metros until the most recent advances and trials in mixed-traffic conditions with Autonomous Vehicles for Collective Transport (AVCTs). It presents a typology of uses with five stages of on-demand services with AVCTs exemplified by many cutting-edge experimentations distributed among the five proposed stages. The arrival of AVCTs shows an imminent disruption in the history of public transport, reconfiguring not only the forms of use, but also its whole business model structure.

In Chap. 2, Jeehoon Ki presents the evolution of government's policy on AVs since the early 2010s in Asia and Europe. To highlight different approaches, Korean and French cases are selected, and the milestones in the evolution of their policies and legislation are compared. Both qualitative and quantitative ways are employed, and the latter is done by a bibliometric analysis. Korea and France commonly set AVs as a national strategic sector between 2013 and 2014, and large-scale R&D investment schemes, various policy measures, and relevant legislation followed, including various trials for AVCTs. Interestingly, each country takes its own unique. France opted for a demand-pull approach, focusing on making AVs socially acceptable. Korea, by contrast, went with a tech-push approach, focusing on making AVs technologically available. This chapter contributes to a better understanding of the different types of interaction between government's policy and the transformation toward robomobility.

In Chap. 3, Sylvie Mira-Bonnardel and Elizabeth Couzineau analyze the regulatory framework for the deployment of autonomous public transport. After providing a general overview of the international and European organizations involved in regulatory statements and the branches of law framing regulation for public transport, the authors propose a tool to evaluate the level regulatory openness toward robomobility, the ROAD index (the **R**egulation **O**penness for **A**utonomous **D**riving index). Taking into account regulations and policy making processes, the authors distinguished a set of four variables to measure the level of national or local readiness for the implementation of autonomous collective vehicles on open roads. ROAD index helps to evaluate regulation as facilitator or barrier to robomobility and to understand in which way decision makers can leverage on regulation to make it build a favorable framework for mobility innovations.

In Chap. 4, Fabio Antonialli, Sylvie Mira-Bonnardel and Julie Bulteau address the issue of economic impact evaluation of robomobility assuming that the integration of autonomous buses into public networks is mainly dependent on costs and breakeven points for operators and local government. Research quantifying return on investment specifically in academic settings are sparse. This chapter aims to introduce a simulation tool: EASI-AV (**E**conomic **A**ssessment of **S**ervices with **I**ntelligent **A**utonomous **V**ehicles). This is designed as a decision-making tool to support public policies on whether or not implementing innovative mobility services. EASI-AV proposes to (a) assess the global economic impacts of deploying fleets of AVCTs in comparison with traditional public transport modes, and (b) help local authorities to build scenarios integrating autonomous buses into their public network and imagine new business models. The simulation is based on the Total Cost of Ownership (TCO) approach and includes four aspects that may be used independently: (1) fleet size dimensioning, (2) the TCO calculation with internal costs and local externalities, (3) the business model simulation, and (4) the global impact assessment in comparison with other transport modes. EASI-AV was tested with real data from pilot sites in Europe, and the results prove it to be fully relevant.

In Chap. 5, Dimitri Konstantas presents a large-scale European experimentation: the AVENUE project. The AVENUE vision for future public transport in urban and suburban areas is that autonomous vehicles will ensure safe, rapid, economic, sustainable, and personalized transport of passengers, while minimizing vehicle changes and maximizing vehicle utilization. The goal of the project is to provide door-to-door, on-demand autonomous public transport services allowing commuters to benefit from the full capabilities of autonomous busses. However, the road to a public transportation service is not so simple. Legal and regulatory requirements create barriers and obstacles, raising the costs and delaying the deployment of the services. In spite of the efforts from the European Commission for a harmonization of the homologation process, urban public transportation is under national and local legislation, creating a highly fragmented European environment. In this chapter, the author presents the experience in setting up and deploying autonomous buses in two cities, Geneva and Copenhagen.

Part II develops a broader view integrating robomobility in the larger perspective of urban mobility innovation embedded in societal contexts. When new mobility services are incorporated in the city network, this integration takes a step closer to transform the urban public transport. This transformation comes with the integration of a user perspective in the design of mobility solutions and with the development of new business models for public transport targeting the development of more sustainable mobility systems. This part is concluded by a prospective analysis of how governance models can put the user at the center of urban mobility.

Part II comprises five chapters that are detailed hereafter.

In Chap. 6, Ouail Al Maghraoui, Flore Vallet, and Jakob Puchinger deal with the formulation and innovation processes of mobility solutions from the viewpoint of designers (vehicle providers, start-up companies developing digital mobility applications, mobility operators, etc.). It is becoming increasingly important to take the door-to-door experience of travelers, and of other users of mobility systems, into account. The authors advocate that user-centered insights are useful at different stages of a solution development. When mobility solutions are not yet on the market, trials are mostly conducted to evaluate technological maturity (of autonomous shuttles for instance). Testers in these trials can say more about their experience and the value of the solution if asked to. When mobility solutions are on the market, there is a need to capture the experience of travelers and uncover their door-to-door issues through a systemic mobility diagnosis. This type of problem diagnosis can be used to feed innovation approaches, reveal value buckets for companies, and bring meaningful solutions for both travelers and other users. Finally, the authors discuss the applicability and the potential of the recommendations for different mobility stakeholders.

In Chap. 7, Ayman Mahmoud, Tarek Chouaki, and Jakob Puchinger investigate the potential integration of innovative mobility modes with urban public transport. The authors emphasize the design of future autonomous on-demand transportation systems and the interactions of these systems with public transport. These new modes pose several implementation challenges for public transport system design, including strategic, tactical, and operational choices when projecting the implementation. The impact on the overall urban transport systems is considered along with the sustainability issues. The chapter proposes to review the current literature and state of the art, investigates technological developments, and finally develops some visions and research perspectives on the future integration of on-demand transport in public transport systems.

In Chap. 8, Adriana Marotti De Mello, João Valsecchi Ribeiro De Souza, and Roberto Marx discuss how new business models may be integrated into public transport in order to contribute to the development of more sustainable mobility systems. Based on the precepts that Mobility-as-a-Service (MaaS) is a viable alternative to improve the conditions in which public transport is accessed and innovations in public transport play an essential role in the development of sustainable urban mobility in cities, the authors highlight a framework of the barriers and drivers associated with the implementation of these business models, from the firm's level – strategic and operational aspects – to the institutional system level in which these new businesses are part of. The authors rely on examples of new businesses that are being developed in emerging countries like Brazil and China, where public transport represents one of the main alternatives for commuting in large urban centers.

In Chap. 9, Rodrigo Marçal Gandia proposes that the MaaS phenomenon entails the integration of different public and private transport, considering public transport as a backbone. The applicability of MaaS schemes is closely related to efficient public transport networks, which is not a reality in several developing countries. In this chapter, the author presents a new perspective on MaaS. Thus, we believe that for a revolution in public transport, MaaS can be a catalyst. The author considers MaaS as a business model that can be modular and adaptable to several realities. By considering public transport as the backbone (whether efficient or not), its eventual inefficiency can be balanced with the integration of private actors, corroborating with the context of smart cities, and new alternatives for private transport means (e.g., autonomous vehicles and shuttles). To this end, the author considers the theoretical precepts of business ecosystem, product-service system (PSS), eco-innovation, and consumer behavior (via the act of sharing). Approaches like these can guide the applicability of MaaS in the context of smart cities and new business model perspectives, such as Corporate MaaS and Rural MaaS.

In Chap. 10, Danielle Attias addresses the issue of urban mobility governance for public transport innovations. Economic, financial, social, and environmental issues are at the heart of ecological transition programs in many major cities globally. This new governance model concerns public transport and the management of innovative mobility, including mobility on-demand. However, the modes of management of public transport are contrasted, being different according to the geographical location of the city, the citizens' way of life, and the history of each metropolis. What remains common to all cities, however, is an ambition and a desire to integrate in their transport network radical innovations such as autonomous shuttles and digitalization tools such as MaaS. The future of mobility is part of a robomobility approach, including autonomous vehicles. This forward-looking vision will radically challenge the relationships between users, citizens, and city governance.

To reimagine the future of urban public transportation is to rethink the future of cities through new technologies, regulations, user behavior, and business models. If the urban public transport revolution is a story written on a daily basis, there is no doubt that the 2020 pandemic crisis has accelerated the transformation. This book lays bricks and mortar for this new story of urban mobility.

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Our discussions with the Atelier Prospectif de la vie robomobile (Robomobile Life Prospects Workshop) provided a favorable framework for building anticipation scenarios on robomobility. Furthermore, thanks to our meetings with GERPISA (Permanent Study and Research Group on the Automotive Industry and Employees), we were able to open this book to young researchers and continue our reflections on the future of mobility.

At last, we recognize the dynamism and commitment of the European Commission, especially by means of its Horizon 2020 program (H2020[1]) for the various research projects on autonomous vehicles and urban mobility, among which we highlight the AVENUE[2] project through which several contributions for the chapters arose.

[1] European Commission, Horizon 2020 program. Available at: https://cordis.europa.eu/programme/id/H2020-EU.3.4.

[2] This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 769033 (AVENUE project).

Contents

Part I
Robomobility Implementation into Public Transport Networks

Chapter 1
Autonomous on-Demand Vehicles and the (R)evolution of Public Transport Business Models

Fabio Antonialli

Abstract This chapter brings an overview of the evolution of automation in public transport, from the first automated metros until the most recent advances and trials in mixed-traffic conditions with Autonomous Vehicles for Collective Transport (AVCTs). It presents a typology of uses with five stages of on-demand services with AVCTs exemplified by many cutting edge experimentations distributed among the five proposed stages. The arrival of AVCTs shows an imminent disruption in the history of public transport, reconfiguring not only the forms of use but also its whole business model structure.

Keywords Autonomous vehicles · Business models opportunities · On-demand services on public transport · DRT · Public transport

1.1 Introduction

Over the past few years, our society's collective imaginary has been captured by illustrations of modern, bustling cities buzzing with autonomous vehicles everywhere. Car manufacturers and tech giants have been recently competing in a multi-billion-dollar race to make this vision a reality. In the meantime, governments worldwide are busy revising and adapting their legal framework to accommodate the era of robomobility. Thus, the debate has quickly shifted from whether it is going to happen, to when and how it will happen (Viegas, 2017).

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As stated by Mira-Bonnardel and Attias (2018), we may expect in the next 20 years a genuine transformation that may pave the way for a new urban mobility paradigm. For the authors, this revolution of urban areas will likely occur by the arrival of Autonomous Vehicles for Collective Transport (AVCTs).

Indeed, as stated by Merat, Madigan, and Nordhoff (2017), as the implementation of more advanced sensors, radars, and navigation technologies in vehicles increases, there is now a potential for the mass-deployment of a new form of publicly available, electrically operated, driverless minibuses for urban environments. If successfully deployed, these automated minibuses and similar automated vehicles can provide flexible and cost-efficient solutions for serving both peak and off-peak demand, parallel and as feeders to trunk lines (Ainsalu et al., 2018).

In this sense, the technology itself is no longer the major hindrance (Poorsartep, 2014), the main roadblocks that AVCTs are now facing are consumer acceptance and regulatory frameworks (Enoch, 2015; Schellekens, 2015). On the other hand, several studies have shown that autonomous driving has reached a high degree of familiarity among the population. The acceptance rates for fully AVCTs ranges between 68% and 77% (Pakusch & Bossauer, 2017).

Thus, urban centers could strongly benefit from the introduction of AVCTs, since they are able to compete with automobiles by price and even be more effective than traditional public transport buses (by taking 15 instead of 150 passengers), moving on flexible routes instead of fixed ones, and being on-demand instead of on-schedule (Ainsalu et al., 2018). As stated by Fagnant and Kockelman (2018), automated mobility-on-demand is based on the idea of shared fully-automated vehicles which might rapidly induce the shift from privately owned personal vehicles to fleet services by driverless, demand-responsive vehicles, shared among a mix of users.

In this regard, we are on the verge of experiencing a revolution in the business models of public transport operators, having for the first time a customizable, autonomous, on-demand, collective, public, and shared transport solution for passengers.

This chapter aims to provide an overview of the recent evolution of automation in public transport as well as to propose different stages of on-demand services with AVCTs and their respective business models opportunities.

Besides this introduction, in Sect. 1.2, the chapter describes a brief evolution of automation in public transport, dating back to the first automated railway lines, until the most recent advances and trials in mixed-traffic conditions with AVCTs. Section 1.3 proposes a taxonomy for on-demand public transport services and provides examples with autonomous shuttles for the proposed levels. Section 1.4 provides a panorama of innovative business models that can emerge due to the implementation of on-demand autonomous shuttles, and lastly, Sect. 1.5 brings the conclusions of the study.

1.2 (R)evolution of Public Transport: From Rails to Streets

1.2.1 The Evolution of Public Transport Automation – Automation on Rails

The robotics and automation industries have been contributing to many aspects of our daily lives for over five decades now, with several IT-related industries based on mobile information technology emerging due to the so-called fourth industrial revolution (Schwab, 2017). In this context, the transport and mobility industries are no exceptions. In fact, public transport has been ahead of the curve for many years, with records tracing back to 1968 when the world's first full scale automatic railway opened in London Underground's Victoria line (Day & Reed, 2011).

Since then, Grades of Automation (GoA) in railways have been evolving, ranging from GoA 0 – no automation at all, to GoA 4 – fully automated operations without any on-train staff (UITP, 2011). In fact, when considering GoA 4, also known as UTO (Unattended Train Operation), the first commercial lines with this type of technology date back to the early 1980s; a good example is Vancouver's SkyTrain, whose operations began in 1985, and today is the third longest automated metro system in the world (Druker & Nassar, 2016), behind Kuala Lumpur and Singapore.

According to the International Association of Public Transport (UITP, 2011), there are currently over 648 km of GoA 4 automated metro-tracks in operation worldwide, spread over 41 lines that serve up to 644 stations in over 25 cities in the globe, among these: Barcelona, Busan, Copenhagen, Dubai, Kobe, Lille, Nuremberg, Paris, Singapore, São Paulo, Taipei, Tokyo, Toulouse, and Vancouver. According to UITP's estimates, the total number of automated metro-tracks is likely to reach 1400 km by 2025. In fact, if one considers small-capacity private lines (e.g., airport services, people movers), the world today has over 204 fully-automated rail lines to serve passengers.

In this sense, automation in public transport is already commercially available, closer, and more present in peoples' lives than they imagine. However, trains and metros operate in well-controlled environments with fewer uncertainties and external interventions than those faced by cars and buses for example.

That is, urban streets and avenues are much more complex and challenging environments than rails. Automated metros do not have to face level crossings, traffic lights, traffic jams, pedestrians, cyclists, and many other uncertainties and variables that make automation extremely complex for the mixed-traffic environment of cars and buses. However, even in the face of these barriers and challenges, automation has been getting off the rails and into the streets and avenues of cities around the world.

1.2.2 *The Revolution of Public Transport Automation – The Emergence of AVCTs*

The earliest record of Autonomous Vehicles (AVs) dates back to the mid-1970s in Japan, with a prototype capable of tracking white street marks at speed up to 30 km/h. Ten years later, the first car-like robot would emerge in Europe in Bundeswehr University as part of the "Prometheus" project and in America with the project "No hands across America" from Carnegie Mellon University, which has developed a vehicle capable of performing autonomous navigation from Washington DC to San Diego with 98% automated steering and manual longitudinal control (Lima, 2015).

However, the biggest watershed in AVs' research and development happened in 2004/2005 in the United States with a series of annual public challenges, called DARPA Gran Challenges (Gandia et al., 2018), from which countless contributions and advances have been made in vehicle automation, bringing the indoors-laboratory research to the streets and shifting the focus to beyond technological aspects. As a consequence, AVs are today a potentially disruptive and beneficial change to the current transportation business model (Attias, 2017).

Similarly to GoA's typology used for railways, the Society of Automotive Engineers (SAE, 2016) have also created a taxonomy for defining levels of automation for on-road motor vehicles. It comprises six levels, ranging from ZERO (no driving automation) to FIVE (full driving automation). As of 2020, in the current stage of technology development, level 2 vehicles are already being marketed, such as: Tesla's models S, X, Y; Mercedes-Benz's S65; Infinity's Q50S; BMW's 750i xDriv; and Audi's A8 (Antonialli, 2019).

Among the many promised benefits of vehicular automation, one can highlight that AVs would facilitate driving, increase road safety, reduce emissions of pollutants, reduce traffic jams, as well as allow drivers to choose to do different things other than driving. Thus, access to fully automated vehicles would also improve mobility for those who cannot or do not want to drive (Attias, 2017; Enoch, 2015; Schellekens, 2015).

On the other hand, from the technology standpoint, there is still a long way to maturity and reliability of AVs, since – to date – there are no level 5 AVs commercially available (Lambert & Granath, 2020), current AVs require constant human monitoring and are prone to sudden harsh breaks and speed limitations. There are also many security and reliability issues still to be solved, as well as several aspects regarding consumer acceptance and regulatory frameworks (Fagnant & Kockelman, 2015; Pakusch, Stevens, Boden, & Bossauer, 2018).

Furthermore, it is worth highlighting that the current level 2 vehicles already being marketed are private luxury cars aimed at the upper classes of the population. Thereby, Mira-Bonnardel and Attias (2018) highlight that fleets of AVs will not be seen on the roads right away. For the authors, it is likely that the widespread adoption of AVs may firstly be authorized for collective transportation, thus offering a solution for larger cities that struggle to provide adequate public transport to support their residents' needs.

In fact, just as for the rail sector, public urban road transport is also ahead of the curve. Besides the well-advanced tests by Google's subsidiary Waymo (with their 5-seater AVs), within the scope of current deployments, the most widely tested upper-automation level vehicles (SAE's levels 3 and 4) are Autonomous Vehicles for Collective Transport (AVCTs) (Antonialli, 2021; Iclodean, Cordos, & Varga, 2020).

AVCTs are electric autonomous buses equipped with a wide-range of sensors and cameras that today are capable of carrying up to 15 passengers with the main goal of fulfilling the first- and last-mile parts of the commute, as well as micro transit for city centers, central business districts, university campuses, airports, shopping malls, hospitals, etc. (Harris, 2018). By being in the higher automation levels, such vehicles do not require the constant monitoring and intervention of a human operator (in fact, these shuttles don't even have steering wheels or pedals). However, due to current legal restrictions, a human operator must always be on board to take control of the vehicle (with a joystick-like controller) in case of automation failure.

With the aim of carrying out a comprehensive benchmark on experimentations with AVCTs, Antonialli (2021) identified 176 experimentations worldwide that unfold in 142 cities spread over 32 countries enabled by 20 different autonomous shuttles manufacturers (Fig. 1.1). However, not only due to the current technological limitations of automation for mixed-traffic conditions but also due to regulatory constraints and consumer acceptance, only 5.71% of these deployments were regular permanent services (all in dedicated/segregated lanes). The majority were short to mid-term trials (81.15%) with the aim of allowing consumers to examine, use,

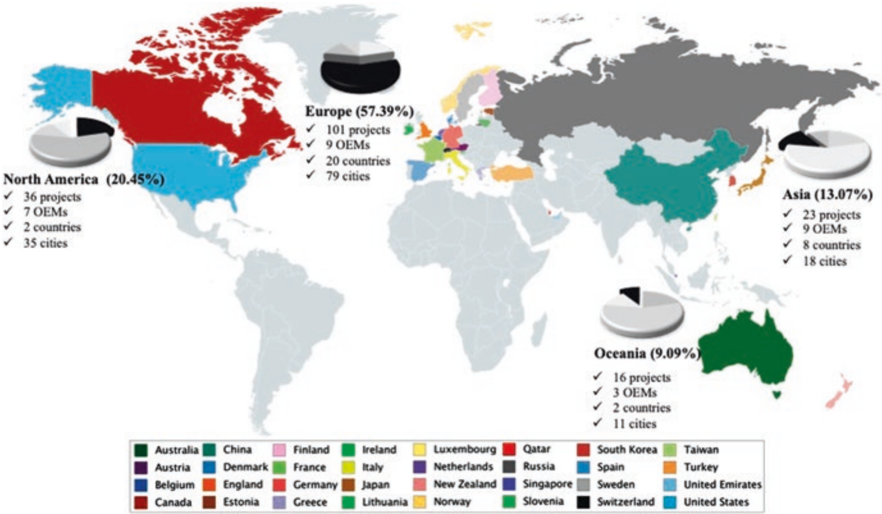

Fig. 1.1 Worldwide experimentations with AVCTs. (Source: Antonialli (2021))

and test the services, and the remaining 13.14% were showcases to promote the technology and the services.

From a historical perspective, one of the first services with AVCTs was offered by the Dutch company 2getthere (Iclodean et al., 2020). Their first applications were pilot tests with automated guided shuttles on dedicated lanes at Amsterdam's Schiphol airport in 1997, and in Rotterdam's business park Rivium in 1999.

In 2006, their services in Rotterdam (operated by the local transport operator Connexxion) were updated with more advanced shuttles and are still commercially operational today. In 2010, the company opened their first permanent system at Masdar City (United Emirates), and today is engaged in delivering the third generation Rivium project, as well as autonomous shuttles at Brussels' Zaventem airport and in the Bluewaters island in Dubai (2getthere, 2018). The company can be seen as the pioneer in commercial operations with AVCTs; however, their main services are offered in dedicated lanes and segregated infrastructures; in this regard, their operations are not yet completely inserted in mixed traffic environments.

On the other hand, the major advances in AVCTs tests in mixed-traffic conditions occurred from 2014 onwards with the emergence of two pioneering French start-ups: Navya and Easymile. According to Antonialli (2021), from the 176 sampled deployments, the two companies together accounted for a total of 78.5% of the number of shuttles used, and more than half (51.13%) of the total of experimentations were in mixed-traffic conditions.

Founded in 2014, with headquarters in Toulouse, EasyMile is the result of a joint venture between Ligier (vehicle manufacturer), and Robosoft (high tech robotics company and former autonomous shuttle manufacturer). Their autonomous shuttle, the EZ10, was developed with the aid of the European Commission funded project CityMobil2 (Alessandrini, 2018). On the other hand, Navya is EasyMile's main contender (Fluhr, 2017). Also founded in 2014, with headquarters in Lyon and Paris, they launched their ARMA autonomous shuttle in October 2015.

Also worth highlighting is the growing relevance of the American market-newcomer Local Motors (Antonialli, 2021; Fluhr, 2017), the company developed their vehicle OLLI, using 3D printing technology and their shuttle is equipped with IBM's Watson artificial intelligence.

Antonialli (2021) also identified that the vast majority of experiments with AVCTs (94.18%) were offered as Regular-Line Transport (RLT) – with predetermined fixed and looped routes, fixed stops, regular intervals between vehicles, and with preset hours of operation. In this respect, RLT with autonomous shuttles already represent an important evolution in the business models of Public Transport Operators (PTOs), not only by bringing high-level automation vehicles to urban roads in mixed-traffic conditions but also by exposing the general public to the technology, allowing them to test and gain more confidence on using these vehicles on a regular basis.

However, the (still latent) potential for a revolution in the business models of PTOs lies on the remaining 5.82% of experimentations that were offered as Demand-Responsive Transit (DRT). In DRT services, by using an app on their smartphones, users can hail an AV according to their specific travel needs (Winter, 2015). Thereby,