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PROMOTING GREEN LIVING AREAS

AMOD Best-Practices Collection

ÉCOLE CENTRALE DE LYON (ECL) | CARNET

ABSTRACT

In Euro-MED region, 40.6 million people live in sparsely populated areas with poor or without public transport services (IEMED, 2021). These areas are expensive for Public (Transport) Authorities (PTAs) to operate due to the low number of paying passengers per kilometre. This leads to high private car dependency or isolation of people (ESPON, 2020), resulting in high carbon emissions (156M tons of CO_2) or inaccessibility to public services and labour market.

A solution recognized by researchers and pilot projects in Europe is Autonomous Mobility on Demand (AMOD), offering higher quality services while reducing operating costs (41% quality-cost ratio improvement, Malmö Uni, 2022) and CO_2 emissions up to 72% (K2Centrum, 2022). However, it is difficult for PTAs to start planning AMOD without the ability to easily estimate its potential socioeconomic and environmental impact.

This deliverable has the objective of presenting the state of the art of On-Demand Transport, as well as Automated Vehicles for Public Transport, and the existing offerings of Automated Mobility on Demand (AMOD). Specifically, it aims at bringing examples of good practices in each of these fields, as well as presenting the main drivers and barriers to their implementation.

KEYWORDS

Autonomous Mobility On Demand (AMOD), Demand-Responsive Transport (DRT), Autonomous Vehicle (AV), Public Transport Authority (PTA), Public Transport Operator (PTO), Public Transport (PT), Best practices, Drivers and Barriers

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1 Executive Summary

In the Euro-Mediterranean region, 40.6 million people live in sparsely populated areas with inadequate public transport services, leading to high car dependency or isolation (IEMED, 2021). This situation results in significant carbon emissions and limited access to public services and the labour market (ESPON, 2020). Autonomous Mobility on Demand (AMOD) has emerged as a promising solution, combining Digital Demand-Responsive Transport (DDRT) and Autonomous Vehicles (AVs). AMOD aims to improve service quality, reduce operating costs, and lower CO2 emissions (Malmö Uni, 2022; K2Centrum, 2022).

The origins of both DDRT and AVs date back to the 1960s and 1970s. Early DRT experiments were informal responses to the lack of transport alternatives for rural areas and people with reduced mobility. Similarly, AV development began in the mid-1970s, but significant transformations in both fields occurred only in the 21st century due to technological advancements.

The advent of mobile technology and routing algorithms has significantly boosted DDRT. By 2023, there were 300 new DDRT projects and over 1,000 active projects globally. Europe and North America lead this growth, with the public sector launching 74% of new projects. Key DDRT providers include Via, Padam, Spare, Liftango and ioki. However, many projects are still in pilot phases, and over 85% operate with fewer than five vehicles, catering to low or irregular demand areas such as rural and suburban regions, night transport, paratransit, and non-emergency medical transport.

AVs saw major advancements following the DARPA Grand Challenges in the early 2000s, leading to real-world applications. The Society of Automotive Engineers (SAE) defines five levels of automation, from no automation (level 0) to full automation (level 5). Currently, level 2 and 3 vehicles (partial or conditional automation) are available, but level 5 AVs are not yet commercially ready due to challenges in security, reliability, acceptance, and regulation. Luxury cars and autonomous shuttles in public transport are the primary beneficiaries of current AV technology. The COVID-19 pandemic led to significant changes in the technology provider landscape, with new players like Nio and Mobileye emerging as leaders.

AMOD, combining DDRT and AVs, is still in its early stages but shows great potential. Some innovation projects have tested autonomous shuttles for collective transport services and assessed user perceptions, which are generally positive. Key issues affecting user acceptance include service quality, operational speed, safety perceptions, and connectivity with other transport services. Users are not willing to pay higher prices for AMOD than for traditional public transport. Large-scale AMOD implementation projects like ALIKE in Hamburg and ULTIMO in Switzerland, Norway, and Germany are currently underway.

The main drivers for AMOD adoption include technological advancements, regulatory support, driver shortages, and changing consumer behaviour. Improvements in sensors, cameras, AI, machine learning, and dynamic fleet management are crucial technological advancements. Favourable public policies at national and European levels provide necessary regulatory support. A chronic shortage of professional drivers, who also represent significant operational costs, is a pressing issue. Additionally, there is a gradual shift from car ownership to mobility as a service.

However, these drivers also present challenges. AV technology still faces reliability, interoperability, and security concerns. Non-standardized regulations and potential conflicts with existing road and driving laws pose significant regulatory challenges. Many users might be reluctant to adopt autonomous mobility on demand due to safety and convenience concerns about not having a human operator on board. Moreover, the acquisition cost of AVs remains high.

Integrating DDRT and AVs into AMOD offers a promising solution to transportation challenges in sparsely populated Euro-MED regions. This approach can improve service quality, reduce costs, and cut carbon emissions. Overcoming technological, regulatory, and societal barriers is crucial for its success. With advancements in AI, machine learning, and AV technology, along with supportive policies, widespread implementation of AMOD is becoming more feasible. Ultimately, AMOD could revolutionise public transport, making it more efficient, accessible, and environmentally friendly, addressing current and future transportation needs.

2 INTRODUCTION

Among the existing range of mobility modes, private cars have historically been predominant for their capacity to transport people from A to B as quickly as possible and with safety, comfort and optimal ergonomics (Antonialli, 2019). In the 1950s there were about 50 million passenger cars globally. By 2014, this number had skyrocketed to nearly 900 million, and it continues to grow at an annual rate of 3%, with projections suggesting 1.3 billion cars by 2030 and 2 billion by 2050 (Gao et al., 2016). This has exacerbated transportation and traffic issues worldwide. In Europe, urban mobility alone accounts for 40% of all CO_2 emissions from road transport and up to 70% (European Commission, 2017).

To address these issues, the focus must shift towards enhancing mobility and accessibility while reducing congestion, accidents and pollution (Cao & Wang, 2017; Ambrosino et al., 2016). Recent decades have seen transformative changes in urban mobility, driven by technological advancements, new business models and societal shifts. Key innovations in public transport include the development of on-demand transport and the advent of autonomous vehicles.

On-demand transport is a flexible, technology-driven service that adapts to customer needs rather than sticking to fixed schedules (UITP, 2021). It enhances traditional public transit, attracts new users and offers efficient service in areas and times where fixed routes are impractical. This model is particularly effective in sparsely populated areas, during off-peak times and for first/last-mile connectivity. Services can vary widely in terms of routes, schedules, fleet size, technology and integration with existing networks (Barrett, Santha, & Khanna, 2019).

Driver salaries are a major expense for transport operators, often making up to 70% of operational costs (Tirachini & Antoniou, 2020). Autonomous Vehicles (AVs) present a solution by reducing these costs and providing flexible, on-demand transport, especially in low-density areas and for first/last-mile trips. Public Transport Operators (PTOs) are exploring AVs for public transit which can autonomously carry up to 15 passengers and offer a personalised, on-demand service, shifting from traditional fixed routes to more flexible micro-transit solutions (Antonialli, 2021).

The integration of Autonomous Vehicles and on-demand services holds the potential to greatly enhance public transport, addressing numerous challenges in developing an economical, sustainable and efficient public transport system, including the current shortage of drivers in the bus sector. This document aims at presenting the state of the art of on-demand transport, autonomous vehicles for public transport, and the combination of both: Autonomous Mobility On Demand (AMOD). It includes examples of good practices in each of these fields, as well as it presents the main drivers and barriers to the implementation of such services.

3 STATE

3.1 DEMAND-RESPONSIVE TRANSPORT (DRT)

Demand-Responsive Transport (DRT) is a category of collective transport services that adapt their operation to the demand from customers in a responsive manner, unlike traditional public transport, which runs on fixed schedules and routes.

Although today the term usually refers to technology-based shared transport services offered through mobile apps, the first documented experiments on DRT date back from the 1960s, generally as uncoordinated and localised responses to the perceived inadequacy of existing transport services in certain contexts, mostly in rural areas or for people with reduced mobility. The formative period of these primal DRT services was the 1970s (Nutley, 1990), when numerous implementations in the form of flexi-route, dial-a-ride and community bus services took place in different countries. For instance, the United States saw the creation of its first dial-a-ride demand response transit agency in Florida in 1970 (Federal Transit Administration), and the UK's first dial-a-ride bus system commenced operations in Oxfordshire in 1972.

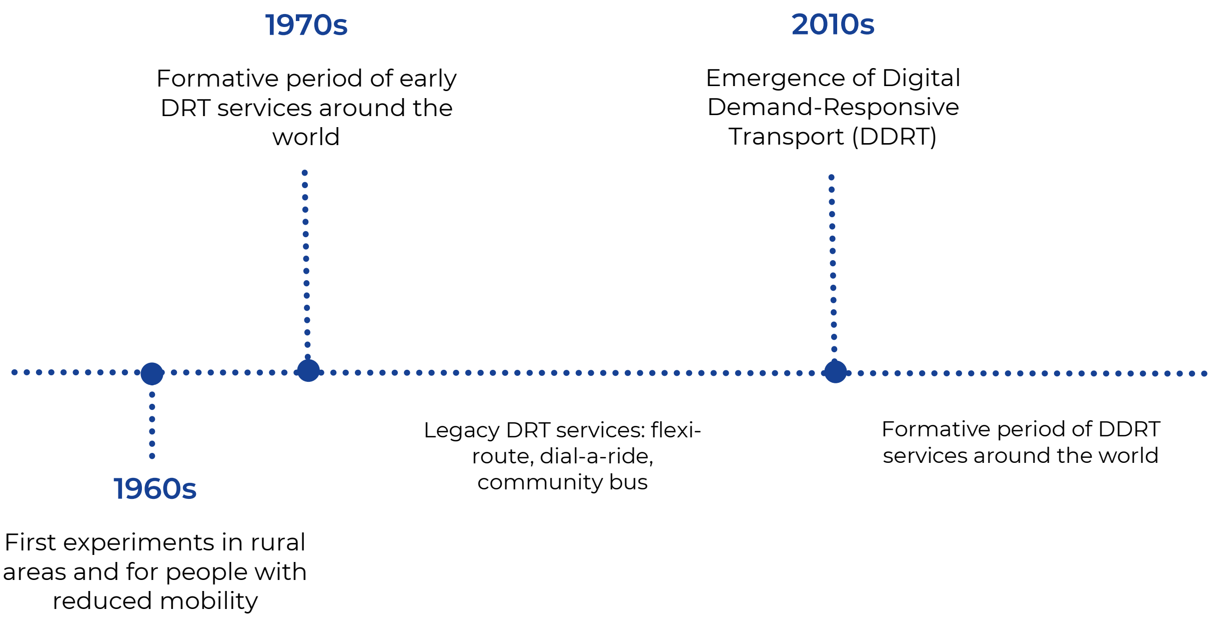

Chart 1. Timeline for the historical development of DRT. Source: own elaboration.

It wasn't until more recent times when the sector experienced a technological revolution which completely changed its landscape. The development and popularisation of mobile devices, equipped with sensors and connectivity, and the advances in research on routing algorithms for collective transport vehicles enabled DRT services to process data and make decisions in real time. This new context led to the creation and commercial exploitation of numerous DRT software companies, giving way to a new wave of DRT services and modalities which coexist to date with the previously existing, more rudimentary schemes. To differentiate them and preserve the legacy of the latter, which still serve a very important social role in the form of community transport, a term that is becoming popular in the UK to refer to the new technology-driven services is Digital Demand-Responsive Transport (DDRT).

The most comprehensive, up-to-date publicly available database of existing DRT services worldwide is the On-Demand Ridepooling World Map, created and maintained by Lukas Foljanty through the information provided by DRT providers and operators themselves. According to his latest report on the DRT market evolution, the year 2023 not only saw more DRT services being deployed than ever —300 new project launches, breaking 2022's record of 298 launches—, but also broke the record mark of 1,000 active DRT services worldwide. Per region, Europe and North America are the biggest contributors to the growth. Regarding market segments, as in previous years, the most important driver of growth was the public sector, contributing around 74% of the new project launches.

On-demand public transport entails a form of publicly subsidised transportation that carries multiple passengers within a defined area from one point to another, according to Barrett, Santha, and Khanna (2019). This mode of transportation becomes pertinent in scenarios where there isn't adequate demand for frequent, direct mass transit solutions (Mulley et al., 2012). Its focus lies in streamlining journeys for groups of passengers travelling to or from a central hub at a subsidised rate. Consequently, when compared to ride-hailing services like Uber, Didi Chuxing, Lyft, and taxis, this may result in comparatively longer wait and travel times.

> **"The year 2023 not only saw more DRT services being deployed than ever — 300 new project launches, but also broke the record mark of 1,000 active DRT services worldwide."**

It's crucial to recognize the diversity within on-demand services for public transport. As stated by Barrett, Santha, and Khanna (2019) variations in business models and service levels can be significant, depending on various factors such as route type (flexible, fixed, or semi-fixed), scheduling (flexible or fixed), fleet composition (size and diversity), integration with existing public transport networks (supplementing or replacing routes), technological features (digital platforms integrated with PTO apps or standalone applications), service coverage (urban core, urban fringe, rural areas), and branding choices (distinct branding for DRT services, disclosure of platform providers, etc.). In this context, Figure 2 classifies and summarises the different operational schemes among which PTOs (Public Transport Operators) can choose when implementing DRT in their local communities.

Level 0

Fixed route with fixed stops

- Service works as a metro, always stopping on each stop;
- Follows a fixed looped route;
- Has fixed frequency (timetable);
- Has fixed operating hours.

Level 1

Fixed route with on-demand stops

- Service works as a regular city-bus, doesn't stop on each stop, only when requested;
- Follows a fixed looped route;
- Has fixed frequency (timetable);
- Has fixed operating hours.

Level 2

Fixed route with flex detours and on-demand stops

- Service works as a regular city-bus, doesn't stop on each stop, only when requested;
- Follows a fixed looped route but can take detours on pre-programmed routes and according to stop requests;
- Has flexible frequency (adaptable timetable);
- Has fixed operating hours.

Level 3

Geofenced flex route with flex on-demand stops

- Service works as a regular city-bus, doesn't stop on each stop, only when requested;
- Doesn't follow a fixed looped route, runs on a mapped grid with pre-programmed routes and pre-programmed stops;
- No fixed frequency (timetable);
- Operating hours may be fixed or not.

Level 4

Geofenced free-floating with flex routes and on-demand stops

- Service works as a free-floating taxi;
- Does not follow a fixed looped route, runs on a fully mapped geofenced area and is able to provide hub-to-hub and door-to-door trips.
- No fixed frequency (timetable);
- No fixed operating hours.

Regular-Line Transit (Levels 0–1)

Demand-Responsive Transit (Levels 2–4)

Figure 1. Typology of DRT services. Source : adapted from Antonialli (2021b, p.11).

In an exercise of characterising the typical DRT project, public or private, with regard to some of the variables mentioned before, it is worth noting that, according to Lukas Foljanty's 2023 recap of the DRT global market evolution:

- Despite the sector's consistent growth, over 50% of the new projects launched are pilots.
- The size of the services launched is usually very small, with around 85% of them having less than 5 vehicles in operation.
- Half of the projects from a sample of almost fifty DRT operations selected by the author from different countries around the world have less than 2 passengers per vehicle and hour.

Regarding the first point, the question that might come to mind after a bit over a decade of DDRT services on the market is: why are we still seeing such a high proportion of projects being launched as pilots? Moreover, many of these projects remain in pilot stage for indefinite time or are even discontinued after some time running as pilots. Some of the most frequently observed reasons explaining this are:

- The financial resources backing the service were framed within an innovation project or programme with limited duration and/or funds.
- The service was implemented within a sandbox framework but there is not an adequate regulatory landscape and/or financial support mechanism that enables its commercial deployment and future economic viability.
- The ridership levels achieved by the service were not up to the expectations of the PTA or public administration funding the service. This could be caused, at the same time, by different factors, mainly: not having based the decision of launching the service on a previously identified need or supply and demand gap; insufficient and/or ineffective communication efforts towards the target users; and lack of understanding of the benefits and use cases associated with DRT, leading to misaligned expectations regarding ridership and turnover.
- The functional and technical features of the service were not well defined according to the existing needs of its target users and, consequently, the solution implemented did not respond adequately, impacting the service quality and user satisfaction and engagement.

Regarding the last point, while the average ridership of the DRT services analysed in the sample might seem very low compared to mass transport services, this can be understood as a natural consequence of the fact that DRT services are usually meant for contexts of low or irregular demand, contexts for which mass transport solutions have proven inadequate. As an additional appreciation, it is worth mentioning that the most efficient public DRT services, which are usually operated with minibuses and are optimised for pooling rides over offering short waiting and travel times, are showing ridership levels that range between 10 and 15 passengers per vehicle and hour.

A picture of the technology provider global landscape can be extracted from the chart shown on Figure 3, where they are represented by their number of active DRT projects.

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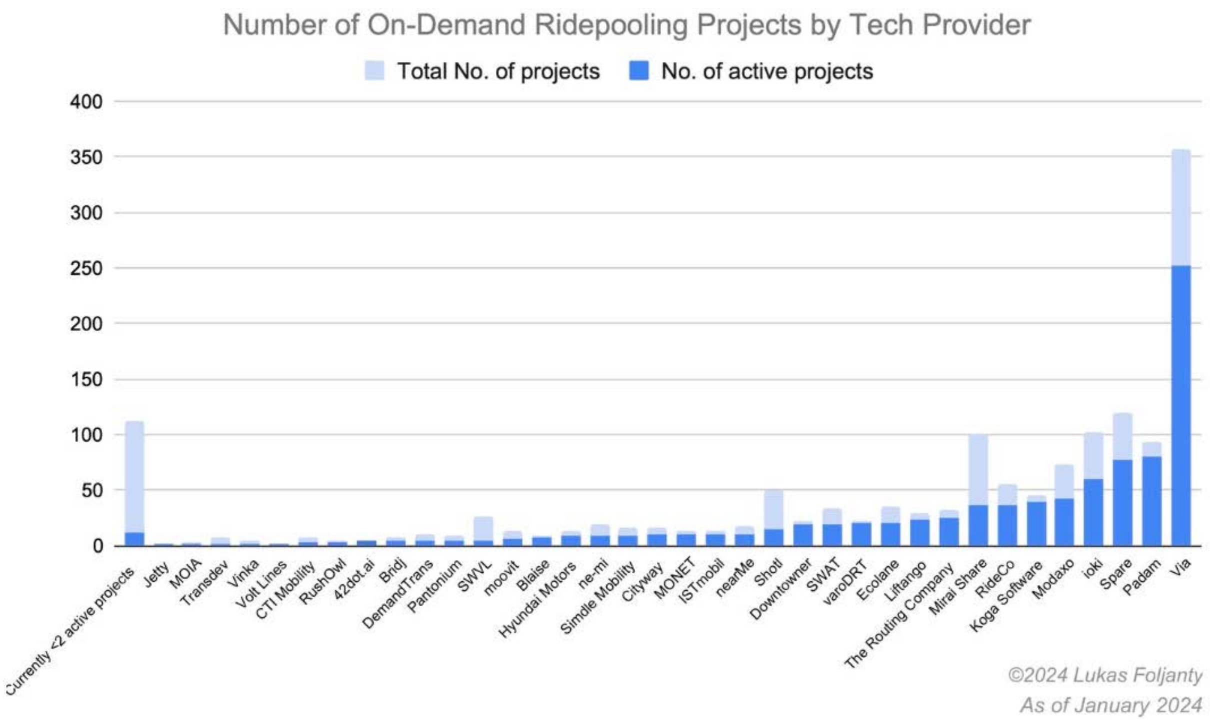

Chart 2. DRT technology providers by number of active projects. Source: Lukas Foljanty (2024).

Via clearly dominates the global DRT market, followed at a significant distance by Padam, which is actually leading the European market a bit ahead of Via. Other technology providers taking relevant portions of Europe's DRT market share are Spare, Liftango and ioki. The most competitive national markets in our continent by number of active technology providers are Germany (home of ioki, which is financially backed by the public transport operator Deutsche Bahn) and the United Kingdom.

To provide an overview of the different contexts in which DRT services are being implemented and the benefits they are providing, Table 1 presents a list of the most relevant use cases and best practice examples for each use case. Additional specific information about the projects selected and many other active projects can be found on the On-Demand Ridepooling World Map.

Use case	Description	Best practices
Rural areas	Rural areas have historically suffered from being underserved by public transport, which has led to higher use rates of private vehicles compared to urban areas. Low population density coupled with the existence of very small and dispersed population settlements make it very challenging for traditional public transport to provide an adequate mobility option, consequently leaving such areas unserved or with a service that is neither attractive nor competitive against private vehicles. DRT services can connect unserved rural areas or provide a more efficient and effective service through flexible or dynamic routes connecting a set of virtual stops on demand. Another usual approach in this context is the operation of fixed routes that are only covered when there is demand for them and in partnership with taxi drivers, for example taking villagers to the closest town for accessing essential services.	“Transporte a pedido” in Médio Tejo, Portugal “Clic.cat” in Girona, Spain Website News article: 42,500 rural dwellers transported by the on-demand public transport service in Girona province in 4 years. “Miobus Oltrepò” in Oltrepò Pavese, Italy
Suburban areas	Suburban areas also face challenges such as lower population density and less availability of essential services	“elMeuBus” in Barcelona, Spain Website

	compared to urban areas. This would be the case of, for instance, peripheral neighborhoods in midsize to big cities, which are usually poorly connected internally and with their city center, or towns within the first and second rings of a big city's metropolitan area. DRT services can make the most of the resources being used for the provision of public transport in such locations, reducing waiting and travel times while increasing coverage and thus reaching citizens who might not have had any convenient public transport available before. These services are usually operated with minibuses of a capacity of up to 30 passengers, which move citizens around the neighborhood and towards public transport hubs that connect them with the city center, acting as a first-/last-mile mobility solution.	News article: expansion of the on-demand bus service in North Barcelona with a third launch since operations started in 2019. "TAD IDFM" in Île-de-France, France Website News article: consolidation and expansion of a successful DRT system in the Parisian region.
Paratransit and Non-Emergency Medical Transport (NEMT)	The term paratransit is generally used to refer to DRT services especially catered to people with reduced mobility, and it originated in the US back in the 1970s. These services rely on the use of vans or minibuses which are adapted for accommodating wheelchairs in their interior, and offer on-demand trips which can be booked	"WirMobil" in Berlin, Germany "Easy Mobil" in Alto Adige, Italy

	via phone call or, more recently, mobile app. The routes are then designed according to the requests received for the day, either manually or by an algorithm in the case of digital paratransit services. A similar case looking at user needs and operational specifications is Non-Emergency Medical Transport (NEMT). Such transport services hold a great potential to be transformed into DDRT, as they are offered only on request and perform manual route design dealing with constant changes in user pools and needs, since a significant portion of them might be under temporary circumstances (e.g. someone undergoing physical rehabilitation after an accident). DDRT would increase the efficiency of operating paratransit and NEMT services while potentially reducing costs and offering real-time service information for users.	
Business parks	The need for better connecting business parks through public transport was clearly exposed during the outbreak of the COVID-19 pandemic. Back then, administrations and PTOs decided to reduce the	"Telekom Shuttle" in Bonn, Germany "SAFIR" in Pau, France

availability of many bus services, even temporarily interrupting service in some bus lines and leaving vulnerable users with no transport alternative for commuting to their workplace. DRT services saw an opportunity there to demonstrate their benefits for bridging demand and supply gaps in contexts of low or irregular demand, especially with workers of essential services in mind, and many pilot projects were implemented during the toughest months of the pandemic.

As the situation was progressively normalizing, transport services that had been affected reestablished their availability, but also experimental pilot projects came to an end, reverting the situation to the original problem: business parks lacked sufficient public transport provision.

The challenge lies in the fact that business parks are usually located on the outskirts of cities and reaching them by public transport involves multiple transfers. Additionally, internal mobility in business parks is not well resolved either, usually lacking a public transport service that can move people between facilities when needed, leading to high rates of private vehicle use for such purposes.

	DRT can be the perfect complement to the existing transport network to solve these challenges.	
School transport	To exemplify how DRT technology can optimize the resources used for the provision of public transport in less dense areas in combination with school transport, imagine a town where all essential services concentrate in the old part of town and many of its citizens live in residential areas somewhat spread throughout the municipal territory. In the morning, kids living in these residential areas will need to be moved to their schools, located downtown, and back to their homes in the afternoon. This generates two very specific moments of peak demand throughout the day, but since we are talking about areas with low population density, the demand for transport during the rest of the day is not enough to sustain a regular bus service for the general population. In response to this, and before the spread of DDRT, local administrations and operators have taken an informal approach by letting people in need of a bus service for their commute use the school bus service at the same time as kids are being transported to	"ValliBUS" in Vallirana, Spain "fflecsi bus" in Wales, United Kingdom

	their schools. Now that more modern technology is available, we are seeing cases (such as the first best practice example presented here) where DDRT is allowing municipalities as the one exemplified before to provide a bus service for the general population taking the same vehicle and driver used for school transport and extending the service hours under an on-demand operational scheme, while keeping the regular operation during rush hour.	
Night transport	Night bus services are an essential piece of public transport networks when it comes to guaranteeing the right for mobility for the most vulnerable users. We are talking about people with mobility needs during nighttime who cannot rely on a private vehicle at a time when most of the public transport choices are beyond their service hours. DRT services can play an important role in improving night transport services regarding two main aspects: reliability and safety. On one hand, the most advanced DDRT services can process immediate trip requests and real-time information, making it a reliable service in the sense that users can trust it will be available for them when they need it and, additionally,	"Tuobus" in Piacenza, Italy "Hin&Wech" in Neumünster, Germany

	they will be informed at all times of the status of their trip and the location of the vehicle. On the other hand, thanks to the fact that DRT services are not tied to fixed routes, transport planners can increase the availability of stops with the objective of bringing users closer to their final destination and thus increasing their safety, which is especially important for women travelling alone at night.	
Tourist destinations	Locations that attract lots of tourism must deal with the negative consequences that dense agglomerations of people have on the mobility of the territory during high season, mainly congestion and parking problems. To counteract such issues, public administrations can opt for a combination of mobility measures to dissuade people from reaching these tourist destinations in private vehicles. More specifically, parking lots purposely built outside the busiest parts of popular sites for tourism should be coupled with link transportation services to make this option attractive enough for people to use it. DRT is a perfect ally to transport tourists from the parking lot to the tourist destination as they arrive in	"Shuttlemare" in Rimini, Italy "Bus&Go" in Alto Garda, Italy

	their private vehicles. This is the case of the first best practice example presented here, a popular beach destination where parking lots were built for tourists a few hundred meters away from the shore, and a seasonal DRT service with vans to transport people to the coast and other points of interest within the city was put in service.	

Table 1. DRT use cases and best practice examples. Source: own elaboration.

3.2 Automated Transport

Autonomous Vehicles (AVs) date back to the mid-1970s, with significant progress made in the 1980s and 1990s with the development of car-like robots in Europe and America (Lima, 2015). The most significant advancements however occurred in the early 2000s in the U.S. with the DARPA Grand Challenges, marking a watershed moment in AV R&D (Gandia et al., 2018). These challenges spurred countless contributions and shifted the focus from lab research to real-world applications, positioning AVs as potentially disruptive solutions to the transportation business model.

Broader adoption may initially be more feasible through public transit solutions in larger cities with high transport demand.

To better help the industry, governments, and consumers navigate the complexity of automation in transportation, the Society of Automotive Engineers (SAE, 2016) has developed a taxonomy for defining levels of automation in on-road motor vehicles, ranging from zero (no automation) to five (full driving automation). Figure 4 depicts SAE's proposed taxonomy.

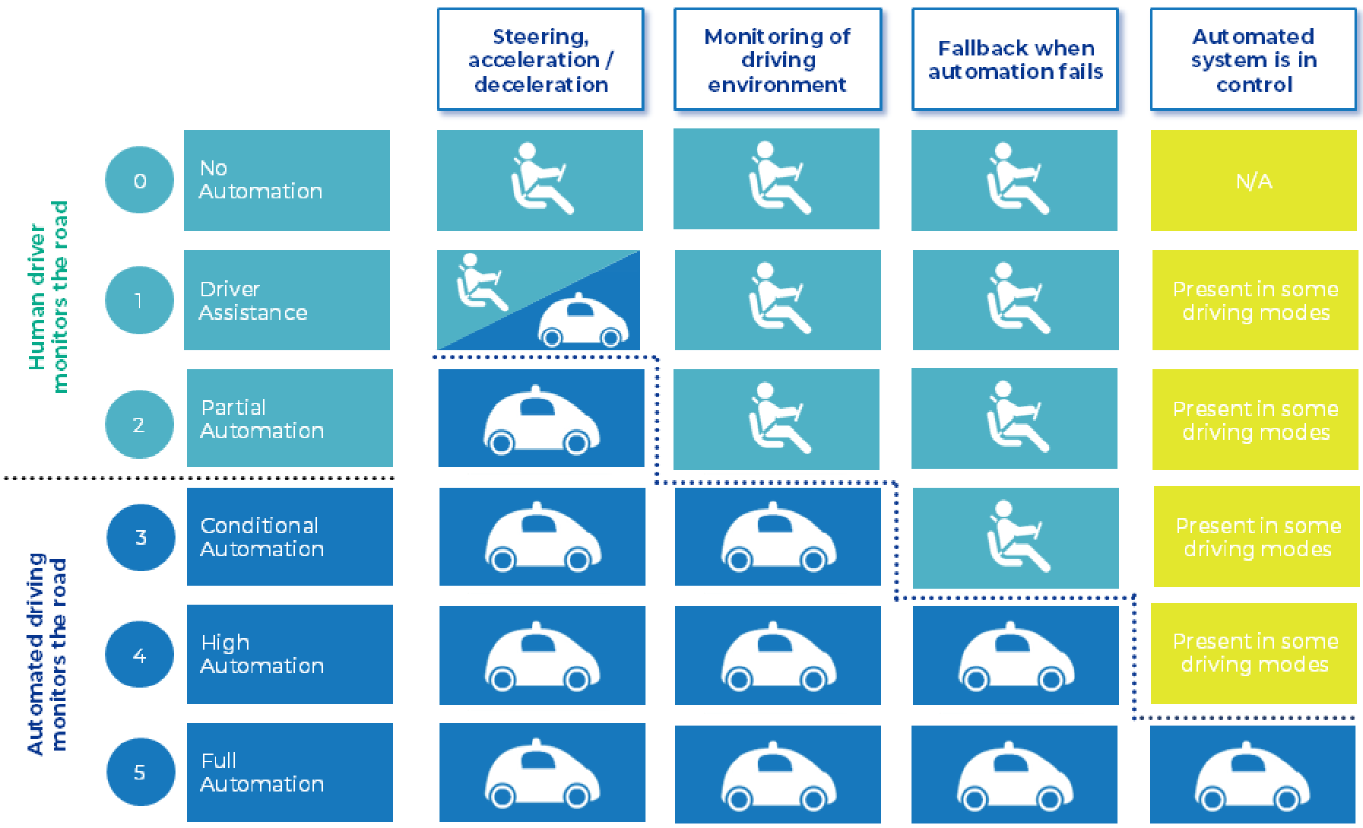

Figure 2. SAE's automation levels. Source: adapted from SAE (2016).

As of 2024, level 2 and level 3 autonomous vehicles, such as those from Tesla, Mercedes-Benz, BMW, and Audi, are available on the market. These vehicles still require constant human monitoring and have limitations such as sudden harsh braking and speed restrictions. Currently, there are no level 5 autonomous vehicles available, indicating that the technology is not yet fully mature or reliable (Lambert & Granath, 2020; Antonialli, 2019). Moreover, issues related to security, reliability, consumer acceptance, and regulatory frameworks remain unresolved (Pakusch et al., 2018; Fagnant & Kock Elman, 2015). The available AVs are mostly luxury cars aimed at the upper classes, suggesting that broader adoption may initially be more feasible through public transit solutions in larger cities with high transport demand.

Research by Merat, Madigan, and Nordhoff (2017) highlights that advancements in vehicle technology, including improved sensors, radars, lidars, and navigation systems, could enable the mass deployment of electrically powered, autonomous vehicles for public transportation. These autonomous shuttles could potentially offer adaptable and cost-effective transportation solutions for peak and off-peak times, addressing first- and last-mile needs, and providing micro-transit options for city centres, peri-urban areas, business districts, university campuses, airports, shopping malls, and hospitals (Ainsalu et al., 2018; Harris, 2018).

Additionally, it is worth noting that higher automation levels do not necessarily guarantee better service performance. Factors such as the manufacturer's background (whether a small startup or a large OEM) and the quality of onboard algorithms and sensors can lead to significant performance variations between vehicles of the same automation level.

Autonomous Vehicles for Collective Transport

Pre-COVID advancements

In a 2021 study, Antonialli (2021) conducted a comprehensive benchmark on the global advancement of autonomous shuttles in public transport, identifying 176 experiments across 142 cities in 32 countries. Europe led this field with 101 trials, reflecting its prominent role in Autonomous Vehicle research and development for collective transport (see figure below). These projects were significantly supported by the European Commission's Horizon 2020 program, with French manufacturers Navya and Easy Mile providing most of the shuttles. Despite the advancements, many regions still required human intervention due to legal restrictions in mixed-traffic conditions (Peng and Sarazen, 2018; Threlfall, 2018; Parker et al., 2017; Fagnant and Kock Elman, 2015; Schellekens, 2015).

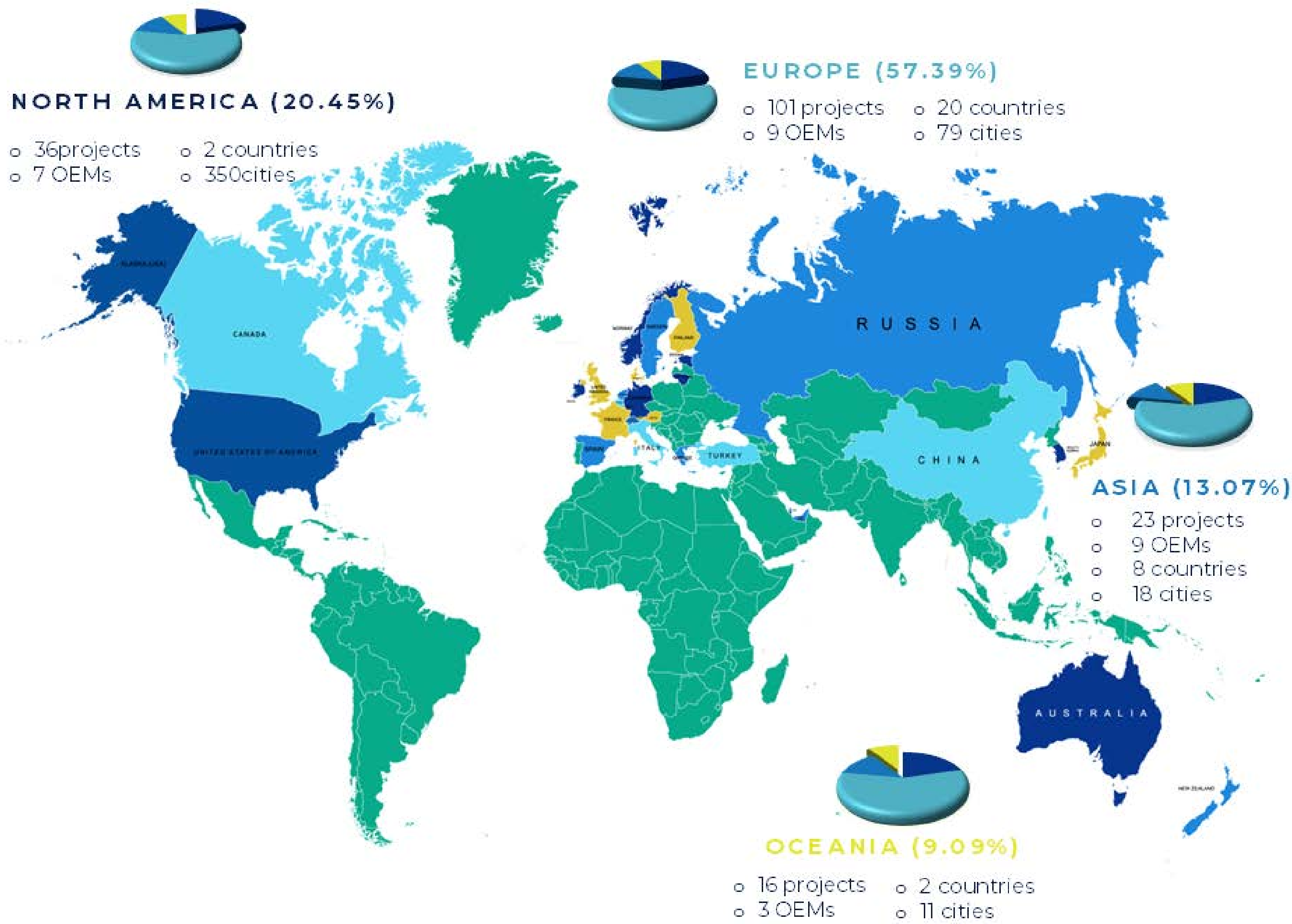

Figure 3. Worldwide experimentations with autonomous shuttles. Source: Antonialli (2021).

The study highlighted two key projects: CityMobil2 and SOHJOA. CityMobil2, funded by the European Commission and operating from 2012 to 2016, tested automated shuttles in seven European cities. It aimed to assess the socio-economic impacts and establish a legal framework for autonomous vehicles. The project drove over 25,000 km and transported more than 60,000 passengers, identifying barriers such as the lack of implementation and legal frameworks, and the need for a better understanding of economic impacts (Ainsalu et al., 2018).

"Global advancement of autonomous shuttles in public transport, 176 experiments across 142 cities in 32 countries. Europe led this field with 101 trials, these projects were significantly supported by the European Commission's Horizon 2020 program"

The SOHJOA project, which ran from 2016 to 2018 in Finland, introduced autonomous shuttles in mixed traffic. It focused on last-mile transportation across three cities and addressed harsh Finnish weather conditions, suggesting that successful trials in such environments could be replicated elsewhere. SOHJOA facilitated innovation by allowing companies to test smart mobility products, leading to the creation of new startups and a Smart Mobility Innovation Hub. Its success led to the SOHJOA Baltic initiative, which aimed to extend trials to additional Baltic cities.

User acceptance studies from both projects showed positive attitudes towards autonomous shuttles, with users finding them convenient and safe. However, there was a need for improvements in service quality, such as operational speeds and comfort. Although economic impacts were less explored, users preferred affordable services and valued service quality over fare reductions. Overall, these projects highlighted the need for reliable performance, robust legal frameworks, and public engagement to enhance the adoption of autonomous shuttles.

"These projects highlighted the need for reliable performance, robust legal frameworks, and public engagement to enhance the adoption of autonomous shuttles."

	CityMobil2	SOHJOA
Duration	2012 to 2016	2016 to 2018
Location	Seven European cities	Three Finnish cities
Funding	European Commission	European Commission
Focus	Automated shuttles, socio-economic impacts, and legal framework	Autonomous shuttles in mixed traffic, last-mile transportation
Key achievements	Drove over 25,000 km, transported more than 60,000 passengers	Tested in harsh weather conditions, led to new startups and a Smart Mobility Innovation Hub
Barriers identified	Lack of implementation and legal frameworks, need for better economic impact understanding	Not specifically mentioned, but involved harsh weather challenges
Follow-up initiatives	None mentioned	SOHJOA Baltic, extending trials to additional Baltic cities

Table 2. Factsheet of CityMobil2 and SOHJOA projects. Source: own elaboration.

COVID-19 Impacts on Autonomous Shuttles Trials

The COVID-19 pandemic has disrupted many ongoing trials and deployments of autonomous shuttles, leading to delays and cancellations due to travel restrictions, lockdown measures, and safety concerns.

Economic uncertainty caused by the pandemic has also led to challenges in terms of funding for autonomous shuttle projects, with some initiatives facing budget cuts or delays in securing investment. Shuttle manufacturers have also been impacted, with Navya announcing in April 2023 its partial takeover of its activities by Gaussin-Macnica-Mobility, and its delisting because of its judicial liquidation (Navya, 2023), and Easy Mile being less requested in trials and projects.

Reduced passenger demand for public transportation during the pandemic has also affected the viability of autonomous shuttle services, leading to decreased ridership and revenue for operators. At last, the pandemic has diverted regulatory attention and resources away from autonomous vehicle initiatives, delaying the implementation of supportive policies and regulations necessary for widespread deployment.

Shuttle manufacturers have also been impacted, with Navya announcing in April 2023 its partial takeover of its activities by Gaussin-Macnica-Mobility, and its delisting as a result of its judicial liquidation (Navya, 2023), and Easy Mile being less requested in trials and projects.

3.3 Automated Mobility On-Demand (AMOD)

Going back to the benchmark study proposed by Antonialli (2021), the author identified that from the total of 176 experimentations, the large majority of 94.18% offered services as Regular-Line Transport (RLT), with predetermined fixed and looped routes, fixed stops, regular intervals between vehicles, and with fixed hours of operations. In this regard, the still latent potential for a revolution in the business models of Public Transport Operators lies on the remaining 5.82% of the sampled experimentations, that offered some level of Demand-Responsive Transit with the autonomous shuttles.

Regarding DRT services, at Level 0, services function like a metro system with fixed stops, routes, and schedules, offering no on-demand capabilities. Most automated shuttle projects prior to the COVID pandemic, such as CityMobil2 and SOHJOA, fall into this category. Level 1 services operate like conventional urban bus routes, stopping only when passengers signal. These services maintain fixed routes and schedules but offer some flexibility for passenger boarding. Examples include

Navya shuttles on Singapore's Sentosa Island, the Fabulos project in Helsinki, Australia's BusBot, and 2getthere's ParkShuttle in Rotterdam, which also functions as a DRT system during off-peak hours. Level 2 introduces more flexibility, allowing autonomous shuttles to deviate from fixed routes based on user demand, though they still follow a primary looped route and stop upon request.

From the total of 176 experiments, the large majority of 94.18% offered services as Regular-Line Transport (RLT), the remaining 5.82% of the sampled experimentations, that offered some level of Demand-Responsive Transit with the autonomous shuttles.

Levels 3 and 4 significantly diverge from traditional public transport models, utilising autonomous vehicles (AVs) within geofenced areas without fixed routes or stops. Users can hail these vehicles via smartphone apps, enabling travel within a defined grid. Due to their complexity and current constraints, examples of Level 3 and 4 services are limited, but notable projects include AVENUE, ULTIMO, and ALIKE.

AVENUE project

The AVENUE project aimed to design and carry out full-scale demonstrations of urban transport automation by deploying, for the first time worldwide, fleets of automated minibuses in low to medium-demand areas of 4 European demonstrator cities (Geneva, Lyon, Copenhagen, and Luxembourg) and 2 to replicator sites (Sion, in Switzerland, and Esch Ville, in Luxembourg).

With four transport operators (TPG, Keolis, Holo, and Sales-Lentz), six demonstrator sites (Meyrin and Belle-Idée in Geneva - Switzerland, Décines in Lyon - France, Nordhavn and Ormøya in Scandinavia – Denmark and Sweden, and Pfaffenthal and Contern in Luxembourg), and two replicator ones (Esch Ville in Luxembourg and Sion in Switzerland), the AVENUE services ran from July 2017 (with the debut of the

Meyrin site in Geneva) until October 2022 (some sites like Esch, Contern, and Belle-Idée continue running even after the end of the AVENUE project).

During the project's duration, over 40,000 passengers have been transported across all AVENUE sites, with the shuttles covering over 53,000 kilometres, with an average rate of 76.78% automated driving and only 23,22% manual drive by the on-board operators (Antonialli et al., 2022). From the total of the eight test sites (including the demonstrators and replicators), 6 ran as a fixed route with fixed stops (AMOD level 0: Meyrin, Décines, Pfaffenthal, Contern, Nordhavn, and Ormøya), one ran as a fixed route with on-demand stops (AMOD level 1: Esch Ville), and one with geofenced flexible gridded routes and on-demand stops (AMOD level 3: Belle-Idée).

In Spring 2020, the project initiated its public trials in Geneva, introducing a level 3 on-demand service in the Belle-Idée hospital district. These trials represented the most advanced deployment of autonomous shuttles for public transportation yet, operating as a regular on-demand service within open, mixed-traffic roads (AVENUE project, 2022). With over 9,825km travelled and over 1,700 passengers transported, this pioneering service used a fleet of Navya shuttles, marking the first instance of autonomous shuttles operating without onboard safety drivers. Operating within a geofenced grid of streets, the service offered flexible, on-demand routes to users. Via a smartphone application, users could hail a shuttle to transport them to and from any of the 70 virtual stops within the designated grid. The application provided real-time information on shuttles' locations, allowing users to make informed route requests.

ULTIMO project

As a continuation of the AVENUE project, ULTIMO (set to run from 2022 to 2026) is an EU and Swiss initiative involving over 20 partners from technology, industry, and academia. The partners' common goal is integrating large-scale, on-demand, passenger-oriented automated vehicle services into the traditional public transport network. To achieve this, various cross-sector teams are researching and accompanying the introduction of Cooperative, Connected, and Automated Mobility (CCAM) systems at three selected deployment sites across Europe (Padam Mobility, 2021).

The first deployment site is Belle-Idée, Geneva, where the project will continue the experimentation begun during the AVENUE project. The goal is to integrate AMOD

Co-funded by the European Union

with the current public transport network. As Belle-Idée hosts various amenities such as a hospital, kindergarten, conference centre, and restaurants, to enhance connectivity within these facilities, three autonomous shuttles will operate, offering passengers 100% on-demand services, with no fixed routes and schedules, passengers can customise their rides through a specialised app (ULTIMO, 2022).

In Herford, Germany, the primary objective is to transition AMOD from a pilot phase to a valuable addition to the current public transportation system. The initiative began with trials involving 2-3 shuttles, with the ultimate goal, by the project's end in 2026, of deploying a fleet of at least 15 shuttles. These shuttles will offer on-demand mobility services, serve as first-mile/last-mile feeders to the local train station and bus centre, and bridge the gap between rural areas with limited bus services and the city centre (ULTIMO, 2022).

Lastly, in the Groruddalen Valley in Oslo (Norway), ULTIMO in partnership with Ruter will pilot a service where customers will have access to AMOD without a safety driver in all traffic scenarios including highways, roundabouts, traffic lights, several lanes, bicycle lanes, pedestrians, etc. The shuttles will also be deployed and operated as a metro feeder service and will replace existing bus lines during low-peak hours (ULTIMO, 2022). Also worth noting Ruter's ambition of deploying in the long-term 30.000 vehicles in their AMOD system (Ruter, 2022).

ALIKE project

By 2030, a partnership between the German Ministry of Transport and the City of Hamburg plans to introduce up to 10,000 autonomous shuttles onto the city's streets. This endeavour, dubbed the ALIKE project, is geared towards revolutionising transportation by introducing AMOD services that complement traditional public bus and rail networks (Connected Automated Driving, 2023).

These autonomous shuttles, operating at SAE Level 4 autonomy, will be accessible via a user-friendly app, ensuring convenient and safe travel for passengers. Spanning three years, the project is backed by six key collaborators, including public transport operator HOCHBAHN, on-demand service provider MOIA, vehicle manufacturers HOLON and Volkswagen Commercial Vehicles, the Karlsruhe Institute of Technology, and the Hamburg Authority for Transport and Mobility Change (Hochbahn, 2023).

With €26 million in funding from the Federal Ministry of Digital and Transport, the consortium will initially deploy up to 20 autonomous vehicles to establish a comprehensive booking and utilisation system, laying the groundwork for future commercial ride-pooling services. This initiative aims to revolutionise urban transportation, enhancing convenience, efficiency, and sustainability for Hamburg's residents and commuters (Sustainable Bus, 2023).

	AVENUE	ULTIMO	ALIKE project
Duration	July 2017 - October 2022	2022 - 2026	By 2030
Objective	Full-scale demonstrations of automated minibuses in Europe	Integrate on-demand automated vehicle services into existing public transport networks	Deploy up to 10,000 autonomous shuttles in Hamburg
Locations	4 demonstrator cities (Geneva, Lyon, Copenhagen, Luxembourg) and 2 replicator sites (Sion, Esch Ville)	3 sites: Belle-Idée (Geneva), Herford (Germany), Groruddalen Valley (Oslo)	Hamburg (Germany)
Level of service	Level 0 (fixed routes/stops), Level 1 (fixed routes/on-demand stops), Level 3 (geofenced flexible routes)	Level 1 & 3 (Belle-Idée), transition from pilot phase to public transport system in Herford, and Level 4 (Oslo)	Level 4 (autonomous with no safety driver)
Key features	Over 40,000 passengers, 53,000 km covered, varied levels of automation,	Continuation of the AVENUE project	Up to 20 autonomous vehicles initially, app-based service, focus on ride-pooling and

	on-demand service in Belle-Idée		complementing public transport
Main funding	European Commission	Fully on-demand services in Geneva, expansion in Herford and Oslo, integration with existing transport networks.	€26 million from Federal Ministry of Digital and Transport
Notable achievements	First instance of autonomous shuttles operating without onboard safety drivers	European Commission	Ambitious large-scale deployment and revolutionary urban transportation system

Table 3. Factsheet of AVENUE, ULTIMO, and ALIKE projects. Source: own elaboration.

4 Drivers and barriers on AMOD

Autonomous mobility on demand (AMOD) refers to transportation services where autonomous vehicles are provided to users on an as-needed basis, often through a smartphone app. Several factors are driving the development and adoption of AMOD services.

The European project AVENUE (2018-2020) showed that, in Europe, the regulatory framework does not facilitate, and in many cases simply does not allow, the full exploitation of autonomous vehicle capabilities for public transportation, while the public transportation services' quality to which the European citizens are used is not easy to achieve with the existing technological state of art, requiring new innovative services that will offer passengers the same quality level as traditional transportation services (Konstantas, 2021). In 2024, different drivers should facilitate AMOD deployment while many barriers still need to be removed.

4.1 AMOD deployment drivers

Technological advancements

To achieve a high level of efficiency and security, three levels of control can be distinguished: micro-navigation, macro-navigation and fleet orchestration. Micro navigation is fully integrated in the vehicle and implements the road behaviour of the vehicle; micro-navigation will provide the required obstacle recognition and bypassing, lane changing (when authorised), turning points, speed control etc. Macro-navigation is the same function as the widely used GPS navigators that provide to the vehicle instructions of the road to take, but are not interfering to the on-road decisions. The fleet orchestration system manages the choice of the specific vehicle that will be used in reply to a specific passenger trip request.

For micro-navigation, the Autonomous Vehicle combines a variety of sensors to perceive its surroundings, such as 3D video, LIDAR, sonar, GNSS, odometer and other types of sensors. Control software and systems, integrated in the vehicle, fusion and interpret the sensor information to identify the current position of the vehicle, detecting and classifying obstacles and objects in the surround environment, and choose the most appropriate reaction of the vehicle, ranging from stopping to bypassing the obstacle, reducing its speed, making a turn etc.

For the macro-navigation, that is the destination to reach and the possible routes to follow, the functionalities are present to both the vehicle and the vehicle management system (at the back-office). The software inside or outside the vehicle decides the best route to follow for reaching the destination and can integrate related information, like blocked roads, traffic jams, and identify a better route for reaching the destination.

Advances in sensor technology, artificial intelligence, and machine learning have made autonomous vehicles more reliable and safer, paving the way for AMOD. Higher connectivity networks like 5G and other high-speed internet connections enable real-time communication between vehicles, infrastructure and control centres, enhancing the efficiency and safety of AMOD services.

AMOD needs a specific fleet orchestration system that considers all available vehicles in the service area, their status (like battery level, passenger service capabilities, number of passengers in the vehicle etc), the passenger requests and needs, and the street conditions, and selects the best suited vehicle to serve a trip request, sending route and stop information to the vehicle (route to follow and destination to reach). The complete planning is dynamically adapted depending on new trip requests, changing street/weather conditions, changes in the vehicle status and operator policies to respect.

Public policies

As cities become more populated, congestion and traffic jams increase, as well as road accidents; local policy makers need to act to change their urban mobility offer. Furthermore, they are expected by their electors to foster change towards a more sustainable and pleasant environment.

AMOD can help alleviate congestion by providing efficient transportation options and reducing the need for individual car ownership. Decreasing congestion consequently reduces greenhouse gas emissions and pollution. AMOD services can accelerate this transition by promoting the use of shared autonomous vehicles on adapted and flexible road routes.

Besides, autonomous vehicles have the potential to reduce the number of accidents caused by human error, which is a significant factor in road accidents. AMOD services can leverage this technology to offer safer transportation options to users. Pedestrian safety is particularly concerned by the arrival of a new generation of LIDARs that extends the usable object identification distance to 80m.

AMOD can offer cost-effective transportation solutions compared to owning and maintaining a private vehicle. Users can pay for the distance travelled or a subscription fee, eliminating the costs of purchasing, insuring, and maintaining a car.

At a regional scale, policy makers shall invest in infrastructure improvements to promote new mobility uses, such as financial bonus for shared mobility, dedicated lanes for autonomous vehicles and charging stations for electric vehicles. These investments are essential for the widespread adoption of AMOD services. AMOD can complement existing public transportation systems by providing first and last-mile connectivity which allows reaching underserved suburban areas. Integrating AMOD services with public transit can improve accessibility and convenience for users.

Lastly, AMOD services can create new job opportunities in the technology, maintenance, and operations sectors. Additionally, they can boost local economies by reducing the need for parking spaces and stimulating other businesses in urban areas.

Regulatory Support

Local policy makers represent an important lever to push national governments and regulatory bodies to support autonomous and shared mobility solutions. They are implementing policies and regulations to facilitate the deployment and operation of AMOD services. In France for example a law was voted in 2018, allowing autonomous public or private vehicles on open roads and targeting 100 to 500 automated passenger transport services, with no operator on board, by 2030 (French Ministry of Ecology, 2023).

In 2018, the European Commission presented a document titled: “On the Road to Automated Mobility: An EU strategy for Mobility of the Future” (EU, 2018). That document proposes “a comprehensive EU approach towards connected and automated mobility, setting out a clear, forward looking and ambitious European agenda" in order to "ensure that EU legal and policy frameworks are ready to support the deployment of safe connected and automated mobility" (EU, 2018). In addition, the Commission published in 2019 guidelines EU approval of automated vehicles (EU, 2019).

Shortage of drivers

The lack of sufficient professional drivers available for passenger road transport is a global and chronic issue that has aggravated with the sector's post-COVID growth, which increased demand for drivers leaving over 80% of European bus and coach operators facing severe, or very severe, difficulties for filling open positions (IRU, 2023).

According to IRU's 2023 European bus and coach driver shortage report, unfilled positions are on the rise in Europe: in 2023, there were 105,000 of them, which represented 10% of the total professional driver population and an increase of 54% compared to the previous year. The shortage is forecasted to get even worse in the coming years, more than doubling by 2028. A contributing factor is the sector's ageing population: less than 3% of bus and coach drivers in Europe are below 25 years old, while more than 40% are over 55. Over 330,000 bus and coach drivers are set to retire in the next five to ten years, while the number of newcomers is significantly lower, which hinders an adequate replacement rate for the existing positions.

The driver shortage can be a driving force for the implementation of AMOD, as it suppresses the driver from the equation and, even if there is a person in charge of safety on board of the vehicle, they do not need to hold a bus driver licence, which makes it easier and cheaper to fill the position. Indeed, the wage of a professional bus driver represents a very significant share of the service operational costs.

Consumer behaviour

Millennials and Gen Z are showing less interest in owning cars and are more inclined towards shared and on-demand services. This demographic shift towards shared mobility is driving the demand for AMOD services.

Moreover, people will appreciate a better coverage of an area with autonomous public transport on demand providing expected advantages like: a higher frequency of service, no rigid timetable but the possibility to call the bus whenever needed, more flexibility regarding the stops/door-to-door service, advantages if the bus is not operated by human driver like a smoother driving style, clear announcements, no more mumbling, no cursing.

Overall, these drivers are contributing to the growth of autonomous mobility on demand, making it an increasingly viable and attractive transportation option for urban dwellers.

While there are many drivers propelling the growth of AMOD, there are also several barriers and challenges that need to be addressed for its widespread adoption, the next subsection goes into details in the most pressing barriers on AMOD today.

4.2 AMOD DEPLOYMENT BARRIERS

Technology reliability and safety

Despite rapid advancements, fully autonomous technology is still in development, and there are concerns about its reliability and safety. Sensors used in autonomous vehicles can be affected by weather conditions like rain or snow, which can hinder their performance.

Autonomous vehicles contain information systems that use sensors and machine learning to drive. These systems need to interact with each other as well as with the surrounding systems. These systems must have interoperability to ensure the systems to be safe and smart. Ensuring that different autonomous vehicles and systems can communicate and operate together seamlessly still appears as a technical challenge.

The green aspect of autonomous electric vehicles could be jeopardised if stronger rules or life cycle analyses were to be applied, or if digital pollution regulation were to be stronger.

Cyber security issues go along with anonymity and personal data protection hardening as well as system's hacking. Autonomous vehicles should be protected against cyberattacks in accordance with established best practices for cyber vehicle physical systems. Vehicle manufacturers still have difficulties to ensure that system updates occur as needed in a safe and secure way.

Digital infrastructures for connectivity, positioning and battery charging are suitable in all urban areas but hardly available in rural areas. Besides, high-definition mapping and precise localization are essential for autonomous vehicles, and creating and maintaining these maps can be challenging.

Public Policies

The main issue surrounding regulation concerns its political aspects. There is an urgent need to introduce convergence into the multilayer's decision-making process between national/regional/local levels and the European level. In many European countries, the distance between the executive and the legislative bodies hinders rapid progress. Besides, AMOD is embedded in the complexity of the political systems of the various states composing Europe.

AMOD is confronted with a lack of European normalisation and standards linked to the various aspects of the autonomous vehicles: homologation process, test authorization, data sharing and common platforms.

At European level there is low consensus on a general framework for regulations governing autonomous vehicles and AMOD services, leading to uncertainty for operators and users.

The existence of transport and mobility policies has a positive impact for the implementation of new services as well as the existence of public service delegation. The existence of an integrator policy organisation at local level implementing local mobility policy has a direct impact on operation efficiency. The local government can fully delegate operations to the integrator and concentrate on needs anticipation and innovation deployment. Therefore, the level of power of a public transport organisation may be considered either a barrier or a facilitator.

Current infrastructure may not be well-suited for autonomous vehicles, lacking necessary infrastructure such as dedicated lanes and communication networks. Autonomous mobility fluidises road traffic but ethical questions are still not solved in case of choices to avoid accidents and operators still encounter difficulties for the fleet management platform to control the routing of the vehicle.

The high cost of autonomous technology and infrastructure investments can be a barrier for local or regional governments and operators looking to launch AMOD services.

The widespread adoption of AMOD could disrupt industries such as transportation, insurance and auto manufacturing, leading to economic challenges. AMOD services may face competition from traditional modes of transportation, including public transit, taxis, and personal vehicles. The AMOD market is rapidly evolving, with new players entering and existing players innovating, leading to intense competition and without proper planning, and shared rules, rapid increase in AMOD services could contribute to urban sprawl and increased congestion.

Regulatory and liability challenges

Current regulations concerning road and driving are clearly in conflict with autonomous vehicles development (Beland, 2005; Mordue, Yeung, Wu, 2020). Autonomous mobility induces a transfer of responsibility from humans to robots which is the very reason for this conflict because existing international laws are based on the concept of responsibility that is very difficult to adapt to robots (Li, Sui, Xiao, Chahine, 2019).

Regulatory and legal issues are one of the main concerns for the introduction of highly automated driving systems. The responsibility and liability of all stakeholders needs to be clear: manufacturers, service providers, government and transport operators need to be aware of their rights and obligations related to the use of automated vehicles.

Determining liability in the event of accidents involving autonomous vehicles can be complex and is still a subject of debate which hinders AMOD deployment. The regulatory framework for autonomous mobility is shaped by the convergence of three main branches of law: the administrative law, the civil law and the criminal law.

The administrative law includes road traffic law in general and covers, among others issues, such as certification and licensing, technical controls, road traffic rules, etc. It deals with stating technical norms as well. The most important legal challenges related to autonomous driving in the area of administrative law are in the field of user requirements as well as use requirements (Fagnant & Kockelman, 2015). There are still different unsolved issues regarding traffic law for autonomous mobility, among which following:

User requirements issues	Use requirements issue
• Does autonomous driving require a special driving licence? If so, shall it be national or international? • Shall an autonomous vehicle driver ("user") be required to have a driving licence at all? • Which is the most appropriate terminology describing the person guiding the autonomous vehicle: driver, supervisor...?	• Do we need any age requirement for autonomous vehicle users? • Should we allow autonomous vehicles everywhere? • Should it be mandatory on special roads or dedicated lanes? • Does autonomous driving have to follow all traffic rules? • If an autonomous vehicle violates a traffic rule, does it have to self-report to authorities? • Should there be an external indicator on the vehicle when operated in autonomous mode?

Table 4. Issues regarding traffic law for autonomous vehicles. Source: own elaboration

The civil law covers legal, the most significant being linked with civil liability: damage and/or injury (hence insurance issues) and product liability (defective product). Two different conceptual approaches could contribute to understanding liability.

The first approach is based on compulsory motor third party liability (MPTL) insurance under the regime of strict liability by mandating autonomous vehicle manufacturers to contribute a portion of the insurance for each individual vehicle. However, manufacturers would be exempted from product liability for injury and damage that is covered under the compulsory MPTL insurance regime and that was caused by a product defect affecting autonomous vehicle functionality, unless the defect is the result of gross negligence. This approach is rather theoretical than pragmatic due to possible administration difficulties.

The second approach suggests product liability to be further sharpened, the requirement of a product defect should be omitted. Instead, the manufacturer should be held liable for injury and damage caused by the way goods acted (i.e. the way of their actions and behaviour; their effect; and the failure of the goods to act or to behave in a particular way, or to have a particular effect). The main argument for this approach is the following: while autonomous vehicles will be much safer than conventional cars, the technology in the product is so complex that there is an uncontrollable residual risk of malfunctioning even when the product is free from defects. Hence, the legislation should introduce an irrefutable presumption of a defect in a highly or fully automated vehicle that causes an accident, unless the manufacturer can prove that the autonomous vehicle functionality was not the cause of the accident. The MTPL regime would, in this alternative, remain identical to the first approach, except that manufacturers would not be incorporated into the MTPL system (Ilkova & Ilka, 2017).

The criminal law concerns the issue of criminal responsibility as well as protection against cybercrime and hackers. In general, research in this area is dealing with the following questions.

- What crimes may be committed with autonomous vehicles?
- Who should be held responsible in case, when using an autonomous vehicle, a crime is committed: the owner; the person who is sitting in the driver's seat (if there is any kind of it), the vehicle manufacturer, the software designer or another entity?
- Will the responsible subject change according to the circumstances and if so, how?
- How should the law react, if the criminally-responsible subject is a legal entity?

As for the criminal responsibility for harm caused by an autonomous vehicle, according to most European states' criminal codes, the driver (or vehicle owner) may be charged with negligence even if the autonomous vehicle was in control (in autonomous mode). In case of no proved negligence, the criminally responsible entity is the manufacturer. Since in most cases, a vehicle manufacturer is a legal entity, it is highly important to consider the issue of corporate criminal responsibility. The European Union countries do not have identical legislation in this area. Personal guilt is the basement of criminal codes in most countries; these codes would definitely need an amendment (Ilkova & Ilka, 2017).

Technology acquisition cost

Due to the novelty and complexity of the technology involved in the operation of AMOD, the acquisition cost that administrations and PTOs must face to adopt this technology is still high, and constitutes a barrier for AMOD's development.

On one hand, there are very few manufacturers of autonomous shuttles with series-production capacity, and the market is so incipient that the low demand does not allow for economies of scale. On the other hand, the technological requirements of autonomous driving, such as complex algorithmics, sensoring and computer vision, make the cost of autonomous shuttles unaffordable for many PTAs and PTOs.

In fact, we are seeing the first commercial implementations of autonomous shuttles for public transport being deployed mostly in Central and Northern Europe, regions with a GDP per capita above the European average. Only as demand for autonomous driving technology increases and its price lowers, will we start seeing AMOD being more widely deployed in Europe and anywhere else.

Public perception and behavioural challenges

Public perception of the safety of autonomous vehicles can be a barrier to adoption, especially after high-profile accidents involving autonomous vehicles. Users also may have concerns about the collection and use of their personal data by AMoD service providers.

In many societies, car ownership is seen as a status symbol, and changing this mindset can be challenging. Users may need to change their behaviour and habits to adapt to AMOD services, which can take time and effort.

Some passengers do not like the idea that there could be no one in the bus to perform first aid if required; they may feel uncomfortable all alone in the bus at night, especially in certain neighbourhoods, and fear vandalism, even robberies or assaults. They'll miss an authority figure present to keep passengers calm and support them during the trip/on board, and especially to get on and off for elders or people with reduced mobility.

Addressing these barriers will require collaboration between technology developers, policymakers, regulators, and the public to create a supportive environment for the growth of Autonomous Mobility on Demand.

	Drivers	Barriers
Technological advancements	Micro-navigation: In-vehicle sensors for obstacle detection and route navigation. Macro-navigation: GPS-like systems for route planning. Fleet Orchestration: Manages vehicle selection and route planning. 5G Networks: Enables real-time communication and enhanced safety.	Technology Reliability and Safety: Issues with sensor performance in adverse weather, interoperability, and cybersecurity. High Acquisition Costs: Expensive technology and low economies of scale.
Public policies	Congestion Reduction: Efficient transportation options. Sustainability: Reduces emissions and pollution Cost-Effectiveness: Eliminates costs of owning a private vehicle. Job Creation: New roles in technology and maintenance.	Regulatory Inconsistencies: Lack of unified EU standards and complex political processes. Infrastructure Gaps: Insufficient dedicated lanes and communication networks.
Driver shortage	Addressing Labour Shortages: Reduces reliance on human drivers, mitigating the impact of the driver shortage.	Driver Shortage: Not a direct barrier but a motivator; severe shortage affects adoption pace.

Consumer behaviour	Shifting Preferences: Millennials and Gen Z favour shared mobility. Service Flexibility: On-demand and customizable transportation.	Public Perception: Concerns about safety and data privacy. Behavioural Resistance: Challenges in changing car ownership mindset.

Table 5. Summary of main drivers and barriers for AMOD implementation. Source: own elaboration.

5 CLOSING REMARKS

As we conclude this comprehensive exploration of best practices for Autonomous Mobility on Demand (AMOD), it is crucial to reflect on the key insights and recommendations derived from this document. The integration of AMOD solutions into urban and rural transport systems presents both significant opportunities and challenges.

The rapid development of autonomous vehicle (AV) technology has laid a robust foundation for the deployment of AMOD services. However, issues related to technology reliability, safety and interoperability remain. Ensuring the seamless integration of various autonomous systems and safeguarding against cyber threats are critical to the successful deployment of AMOD solutions. Additionally, the high acquisition cost of AMOD technology is a major barrier, particularly for public transport authorities (PTAs) and operators (PTOs) in regions with lower GDP. Economic feasibility is closely tied to market demand and production scalability, suggesting that broader adoption will likely drive down costs over time. Furthermore, operational challenges such as infrastructure readiness and the need for dedicated lanes and communication networks are significant hurdles.

The regulatory landscape for AMOD is fragmented and often inconsistent across different jurisdictions. Harmonising regulations at local, national, and European levels is essential to provide clarity and stability for operators and users alike. Policies that support innovation and provide a clear framework for testing and deployment can accelerate the adoption of AMOD technologies. Public acceptance of autonomous vehicles is influenced by concerns over safety, privacy, and the perceived loss of personal interaction. Addressing these concerns through transparent communication, robust safety measures, and user education is vital. Behavioural shifts, particularly in societies where car ownership is a status symbol, will require time and targeted strategies to encourage the adoption of shared autonomous services.

Effective implementation of AMOD requires close collaboration among technology developers, policymakers, regulators and the public. Creating platforms for dialogue and partnership can facilitate the exchange of ideas and foster a supportive ecosystem for AMOD innovation. Governments and private sector stakeholders should invest in the necessary infrastructure to support AMOD, including high-definition mapping, reliable communication networks and dedicated lanes. Additionally, ongoing investment in research and development will be crucial to overcome technological barriers and improve system interoperability and safety.

Policymakers should work towards developing cohesive regulatory frameworks that align across different levels of government. These frameworks should address issues such as data sharing, liability and standardisation to provide a stable environment for the deployment of AMOD solutions. Initiatives to educate the public about the benefits and safety of AMOD are essential. This can include public demonstrations, pilot programs and campaigns that highlight the environmental and economic advantages of autonomous mobility solutions. Engaging with communities to address their concerns and preferences will also help build trust and acceptance. Encouraging early adoption in economically strong regions can create a demand that drives down costs through economies of scale. Incentives and subsidies for early adopters can also play a role in making AMOD more accessible and attractive to a broader audience.

The transition to Autonomous Mobility on Demand represents a transformative shift in how we approach transportation. By embracing the opportunities and proactively addressing the challenges, the way can be paved for a more efficient, sustainable and inclusive mobility future.

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