Analysis of the delayed roll-out of fully autonomous vehicles

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This report analyses and explains the reasons behind the delayed rollout of autonomous vehicles on a large scale. The report delves into technical, commercial, and regulatory challenges and provides suggestions on how to overcome those.

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List of Abbreviations and Acronyms

AD	Automated Driving
ADAS	Advanced Driver Assistance System
API	Application Programming Interface
CRM	Customer Relation Management
DbW	Drive-by-Wire
DRT	Demand Responsive Transport
LOU	Lagen om offentlig upphandling (Swedish law for public tenders)
LUF	Lagen om upphandling inom försörjningssektorerna
NHTSA	National Highway Traffic Safety Administration
ODD	Operational Design Domain
OEM	Original Equipment Manufacturer
PTA	Public Transport Authority
PTO	Public Transport Operator
PUDO	Pick Up and Drop Off Location
SoS	System of Systems
TOD	Target Operational Domain
V2X	Vehicle-to-Everything

1 Abstract

Despite having been on the agenda for a long time and ambitious announcements from industry heavyweights, the widespread deployment of automated driving (AD) technology has still not happened yet.

So, why does the breakthrough of AD always seem to be two years away?

Based on the authors' experience of developing autonomous vehicles (AVs) and the surrounding on-demand mobility service at NEVS and numerous discussions with industry experts, the main reasons are:

Firstly, the overall complexity of the problem and the many interdependencies between different and often otherwise unrelated disciplines which often leads to development in one discipline being hindered by obstacles in other disciplines or areas of expertise.

Secondly, the fact that there's no purpose-built AV available today that has both a design optimized for ridesharing and the technical maturity for AD technology to unfold its full potential. In this case, technical maturity refers both to fulfilling functional safety requirements and readiness for serial production.

This report aims to, with a special emphasis on purpose-built AVs, analyze and explain technical, commercial, and regulatory challenges around automated driving and provides suggestions on how to overcome those. Since many challenges are interdisciplinary in their nature and advancements in one discipline are often hindered by obstacles in other disciplines, this report is intended to give a broad overview and general understanding of as many AV related aspects as possible and to make interdependencies between different areas visible. If you are an expert in one AV related discipline, it's not the authors' ambition to teach you anything new in your specific area of expertise, but for some of the other disciplines they hope the report can provide you with new insights and guidance that will prove valuable for your own work.

This report has been written with support from Drive Sweden, financed by Vinnova, Formas and the Swedish Energy Agency.

2 Introduction

Achieving the agreed upon UN sustainability goals requires a fundamental transformation of the transportation sector and mobility landscape. Mere electrification of vehicles will not be enough and cities will still have problems with congestion (that will not be solved by adding road lanes[1]) and car related infrastructure covering far too much land area. The most straight forward solution to these challenges would of course be for people to switch from their private car to public transport. However, seen through the eyes of a public transport sceptic car enthusiast, public transport could be described as a mobility service that takes customers from where they are not, to where they don’t want to go, at a time they haven´t chosen, together with people they don’t want to be with. And even those that have a less negative opinion about public transport admit that it often lacks the availability, flexibility and comfort to completely out-compete the private car. However, if a flexible on-demand service is combined with smart systems for demand and supply orchestration, with vehicles and services that are designed and developed for ride sharing, and with the reduced cost of not requiring a human driver, this kind of mobility service can certainly be a real alternative to the private car.

Despite having been on the agenda for a long time and ambitious announcements from industry heavy weights, the widespread deployment of AVs has still not happened yet. There have been numerous trials with low-speed shuttle busses and there are first commercial services with retrofitted passenger cars available, mainly in the US and China. But we are still not anywhere near the full potential that could be achieved by combining AD technology, purpose-built vehicles and smart and integrated services.

In addition to in-depth discussions during this project, the authors have asked 25+ industry experts in their network to state the top three reasons for why the deployment of autonomous vehicles is progressing slower than previously expected. The answers vary somewhat depending on the respondents' backgrounds, but there are more similarities than differences, and many of the similarities match quite well with Drive Sweden's thematic areas[2]. Most experts mention that the technical challenges of autonomous vehicles have been underestimated in the past, and that only a few actors now have proven sufficient maturity for commercial deployment. Nearly as many point out the lack of clear market incentives and -rules that result in a (perceived) lack in demand, especially from the public sector, and that politicians and top managers in public and private entities, haven’t fully understood the potential of autonomous vehicles. Several highlight the absence of purpose-built vehicles ready for industrialization, attributing it on the one hand to the fact that mobility as a service based on AVs would require Original Equipment Manufacturers (OEMs) to drastically change their business model and on the other hand to a general lack of appetite for risky long-term investments since the onset of the pandemic. Some experts consider legislation and permitting to be an overrated problem, while others believe that the lack of harmonization between states in the US or countries in the EU is a real issue that slows deployment down.

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[1] It has been known since at least 1930 that adding lanes often makes congestion worse but it’s still proposed as a solution. Report of the Transportation Survey Commission of the City of St. Louis (1930), p.109

[2] Thematic areas | Drive Sweden

Based on numerous discussions with potential investors on behalf of NEVS, the authors can confirm that the perceived potential rewards of AD technology in general and purpose-built AD vehicles in particular have not been a good fit with what investors are currently looking for. The reasons for this may seem to be trivial when considered individually, but most aspects cannot be addressed in isolation and collectively they present a very complex challenge. Many solutions require knowledge beyond one's own expertise and necessitate a deeper understanding of a larger set of systems, technologies, and disciplines. When all known and unknown risks are considered together, the overall business case might appear too uncertain.

Firstly, mobility as a service provided by AVs is **not proven**. From a customer perspective it is a service that, when it works, would be appreciated. But uncertainties remain regarding its utilization, user preferences, and willingness to pay, especially since the service’s main competitor, the private car is certainly an attractive product. Furthermore, if this solution should be part of publicly financed mobility, society and politicians usually require hard evidence on the solution's positive impact on pressing matters like climate change, air quality, congestion, and societal dynamics in general before committing to it.

The **complex** interplay of different technologies and operational aspects further complicates the situation, demanding near-perfect performance from a technical and safety standpoint. The involvement of various stakeholders, including service providers and regulatory bodies, introduces additional uncertainties and potential roadblocks.

The significant **investments** made in the development phase raise questions about the economic viability and first-mover advantage for stakeholders across the value chain. Competing in this evolving landscape requires an attractive service proposition, proven societal benefits, and a clear revenue model, all amidst regulatory ambiguity and intense competition.

Considering these challenges, accelerating development requires stakeholders to be pro-active, but balance risks with opportunities. Public entities must contribute financially to early stage deployments, policymakers are required to craft regulations without a complete understanding of their implications, and industry players must invest in unproven solutions with uncertain returns. Collaboration and adaptation are essential for creating a sustainable mobility ecosystem.

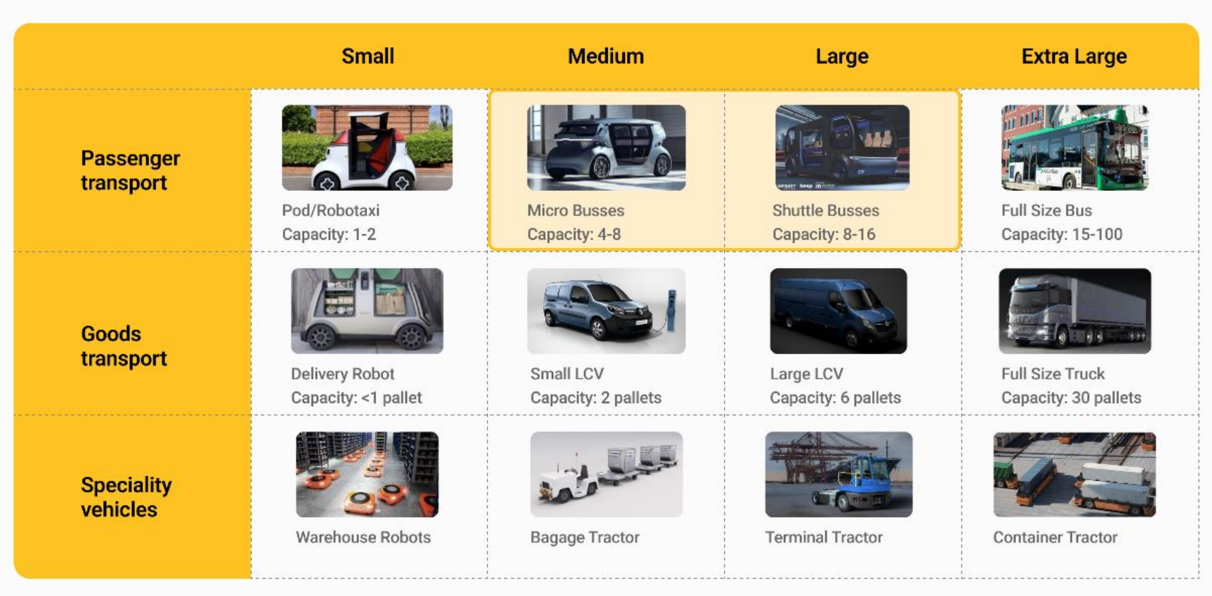
Ultimately, all stakeholders must be willing to adapt their positions, collaborate transparently, and contribute to the evolution of mobility toward a more sustainable future.

2.1 Structure of the report

This report provides an in-depth discussion of the most relevant aspects of the delayed deployment of automated driving (AD) technology in general and purpose-built AVs in particular. The report starts with an AD market overview (Chapter 3) that explains the underlying market dynamics and explores the diverse use cases and roles played by different actors along the value chain. The market overview also addresses geographic variations that cause differences in the roll-out of automated vehicles in different regions of the world.

Chapter 4 gives an overview of the AD ecosystem, with in-depth descriptions of purpose-built AVs, the AD technology itself, mobility services designed around shared AVs, operation of such mobility services, public transport, and relevant legal frameworks as well as related infrastructure. For those parts of the ecosystem as well as additional stakeholders, chapter 5 addresses critical challenges contributing to the delayed roll-out of AVs. Potential solutions are outlined alongside an effect analysis to guide stakeholders through these challenges. Chapter 6 concludes with tailored recommendations to authorities / the public sector, OEMs, fleet operators, service providers, and research institutes.

2.2 Scope & Delimitations



	Small	Medium	Large	Extra Large
Passenger transport	Pod/Robotaxi Capacity: 1-2	Micro Busses Capacity: 4-8	Shuttle Busses Capacity: 8-16	Full Size Bus Capacity: 15-100
Goods transport	Delivery Robot Capacity: <1 pallet	Small LCV Capacity: 2 pallets	Large LCV Capacity: 6 pallets	Full Size Truck Capacity: 30 pallets
Speciality vehicles	Warehouse Robots	Bagage Tractor	Terminal Tractor	Container Tractor

Figure 2-A: Focus areas of the report, source NEVS/ Mobility as a Service AB

The report's focus is on shared and autonomous transportation of people on public roads. It mostly excludes the automation of private cars, as the authors anticipate minimal disruption to the existing mobility landscape from these developments. While the incorporation of level 4 automation in private cars may offer a noteworthy feature to the car owner, the overall business model is unlikely to undergo a substantial transformation (and congestion would probably become much worse if private cars also drive empty). The report excludes the automation of larger buses since the user experience for customers would largely remain unchanged compared to how public transport works today, although fully automated larger busses would certainly be a way solve driver shortages as well as result in cost reductions.

Additionally, fully automated driving can certainly be deployed quicker in some off-road or behind-the-fence applications like airports, mines or warehouses since type approval and related vehicle regulations don't apply. However, the authors don't consider that a large-scale roll-out (and thus, have not included it in the report), since specialized vehicles for niche applications don't have a large enough impact on the overall transport system and people's everyday lives.
To avoid misunderstandings, the authors would like to clarify that when discussing mobility services based on fully autonomous vehicles, they don't refer to the type of fixed route, very low speed demonstrators employing vehicles from suppliers like e.g. Navya, Easymile and Local Motors that have been deployed during the last ten years mainly in Europe but also globally. While these demonstrators certainly were a good way to give authorities and the public a first glimpse of the technology, the vehicles have too basic technical limitations to be a feasible for a larger roll-out.

Rather than to dig deeply into the details of one specific technical or economical aspect of AVs and their deployment, this report is intended to give a broad overview and general understanding of as many AV related aspects as possible. If you are an expert in one AV related discipline, it's not the authors' ambition to teach you anything new in your specific area of expertise, but for some of the other disciplines or areas they hope the report can provide you with guidance and new insights that will prove valuable for your own work.

The report is written from a mainly European perspective, describing the US and Asian market mainly in how they differ from the European market and not as stand-alone analyses.

Since there's many different definitions and usages of the word "robotaxi", the authors would like to clarify that in this report, robotaxi is used to describe an autonomous version of how a taxi or Uber-like service is generally used today, i.e. a single occupant on-demand service with no or comparably little ridesharing.

2.3 Acknowledgements

A special thanks to the following industry experts for contributing to the content of this report through in-depth discussions and answering our many questions (in alphabetic order):

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3 Market

This chapter delves into the market dynamics of innovative mobility services and concepts emerging from the combination of shared on-demand services with purpose-built, fully automated, on-road vehicles. It provides an in-depth exploration of the product market fit, service usage, market structure and potential value of the service, as well as a description of regional differences. This analysis aims to enhance understanding of the evolving dynamics and distinctive characteristics within the autonomous mobility market.

3.1 Product market fit

Different mobility modes have their specific pro- and cons. Some of them are very practical in their nature and some of them are more based on emotions. A possible way of grouping and comparing different modes of transportations is by structuring them according to price per passenger km on the one hand and convenience on the other. Although convenience is of course somewhat broad and subjective, for most people it's some combination of flexibility, comfort/privacy, accessibility, timeliness, reliability, and in some cases even status. Different individuals' different perceptions of "convenience" can be explained by differences in how they value these different aspects.

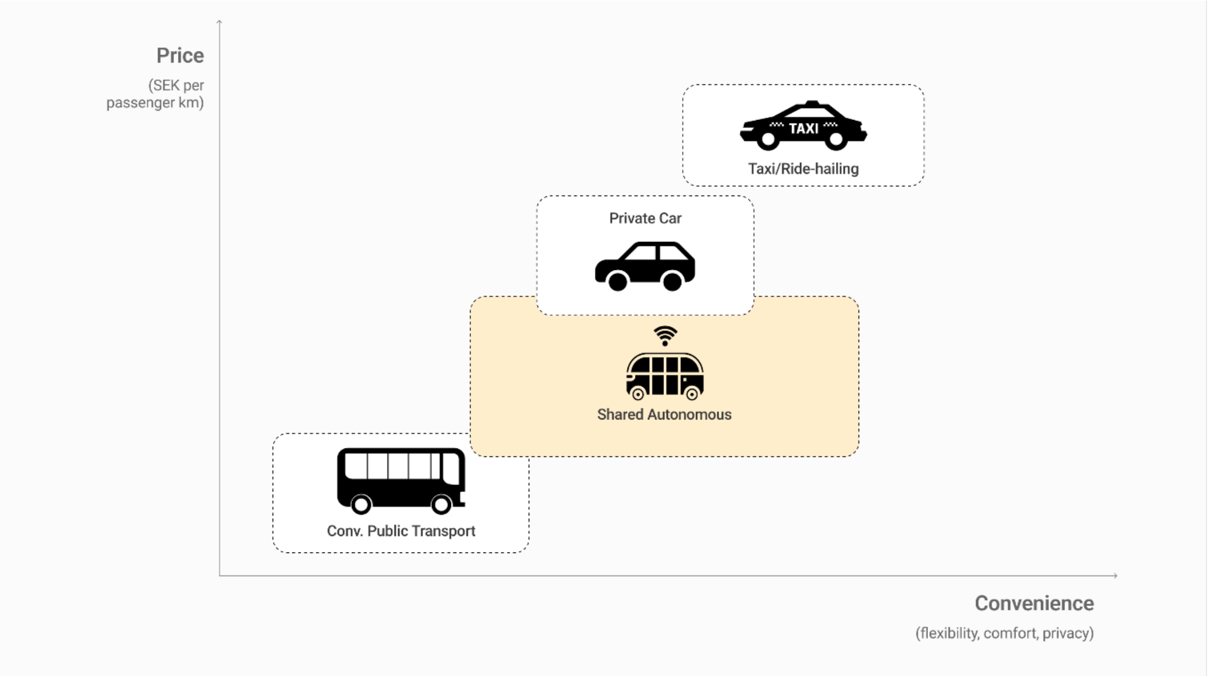

Figure 3-A: Product market fit for shared autonomous vehicle. Source: Mobility as a Service AB

Trains and buses offer the distinct advantage of efficiently transporting large groups of people to and from the same destination simultaneously. Their main benefit lies in their capacity to cover large distances at a low cost per passenger kilometer while also maintaining a low carbon footprint.

The most straight-forward ways to make line based public transport more attractive convert car trips into public transport trips are more frequent departures, bus stops closer to the origin/destination, lower ticket prices, shorter travel times, and avoiding transfers between modes of transportation.[3]

Walking, cycling, e-scooters, and other micro-mobility services contribute positively to the environment, promote personal health, and come at a reasonable price. However, they face limitations in terms of distance, safety, luggage capacity, and convenience, especially in Nordic countries, where it's often cold, rainy, or dark.

Taxi services, particularly those not shared, are expensive per passenger kilometer and are impractical for mass transit.

Private cars offer flexibility, comfort and privacy and allow individuals to travel virtually anywhere. Nonetheless, they are not without drawbacks, both for the individual owner (high costs, ownership hassle and parking challenges) and for society (congestion, land area use, infrastructure cost).

In today's mobility system, there's a large gap between public transport and the private car when it comes to both convenience and price (and price correlates directly with efficiency and to some extent even sustainability) and the type of shared on-demand service that becomes commercially viable through the maturing of AD technology could fill that gap. On-demand services utilizing AVs could be able to strike a balance between traditional public transport and private vehicles, providing a great product-market fit. This emerging category aims to combine the convenience of private transportation with the price, efficiency, and sustainability of public transport.

A factor that can be seen as an aspect of convenience but still needs to be treated somewhat differently than the other more practical aspects is the car as a status symbol. While the high-status appeal of some kinds of cars might be difficult for a shared mobility service to fully replicate, the status factor could also be a way for an autonomous on-demand service to differentiate itself somewhat from traditional (line based, large vehicles) public transport, thereby addressing additional customer groups that seldomly use public transport today.

If positioned like in the above figure, it is of course of utmost importance from a sustainability perspective that the new services don't cannibalize on more sustainable modes of transport, like traditional public transport, biking, or walking. The existing transportation services from which the new solutions capture market share are largely determined by how, where, and to whom the service is offered, at which price, but also who is offering the service. The picture below from Fremmot, a subsidiary to Ruter (the Public Transport Authority, PTA of Oslo and Akershus) illustrates their ambition in positioning shared automated vehicles to mainly take market share from private cars.

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[3] Kollektivtrafikbarometern (svenskkollektivtrafik.se)

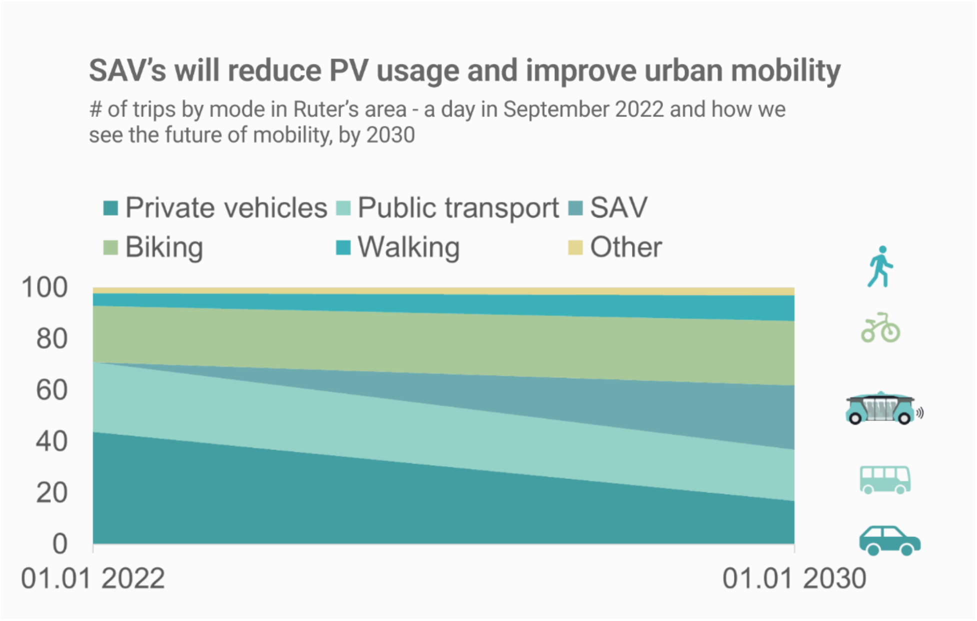

Figure 3-B: Market share for Shared autonomous vehicles. Source: Fremmot

From an OEM perspective this might be seen as a negative development and a risk for the existing business model. For a more detailed discussion of this aspect, please refer to chapter 5.8.

3.2 Use Cases

The basis for any mobility offering is that people have the need to move from A to B. Each person has distinct mobility requirements, be it commuting to work or school, leisure trips, or running more practical daily errands. Moreover, individual preferences vary significantly, encompassing factors such as time constraints, convenience, privacy, and cost considerations. Individuals often weigh these factors differently based on their unique circumstances and priorities, resulting in a diverse array of travel behaviors within any given population.

According to Trafa[4], over half of all journeys in Sweden revolve around commuting to and from work or school, with the automobile standing out as the prevailing mode of transport. The most important factor shaping an individual's travel choices is whether they live in or around a city or in more rural areas. In metropolitan areas, public transport, cycling, and walking are more prevalent, whereas private cars are of greater importance in rural areas. Additionally, life situations play a role in travel mode preferences, with families, particularly those with children, leaning toward the frequent use of private cars. Although the image below is specific for Sweden, the same patterns can be found all across Europe.

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[4] Trafikanalys – en kunskapsmyndighet för transportpolitiken (www.trafa.se)

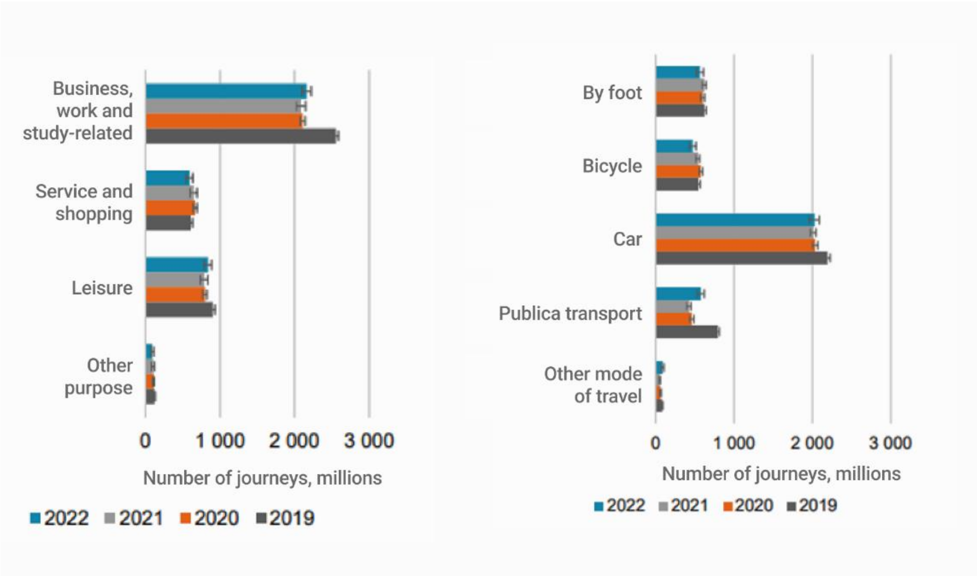

Figure 3-C: Purpose for travel and mobility mode. Source: Travel survey (trafa.se)

Public transport often solves/focuses on journeys to and from work and school but is, in many cases, not a satisfying solution for leisure travel and daily errands. Private cars have the benefit of solving all or most of the use cases in daily life and that's one central reason for households to own a car (or in many cases even two cars). So, any mobility service or mix of services that intends to compete with the private car needs to cover all or most of the use cases and mobility needs, and not only focus on the ones with the highest willingness to pay or demand in passenger km.

Larger cities, medium size cities and smaller communities/rural areas

About 80% of European citizens live in cities, yet the precise definition of a "city" requires further clarification. In Sweden, roughly 88% of the population lives in what is classified as a city or "tätort". However, when considering the size and characteristics of these cities, it may not align with many people's definition of a city since many of them are rather small.

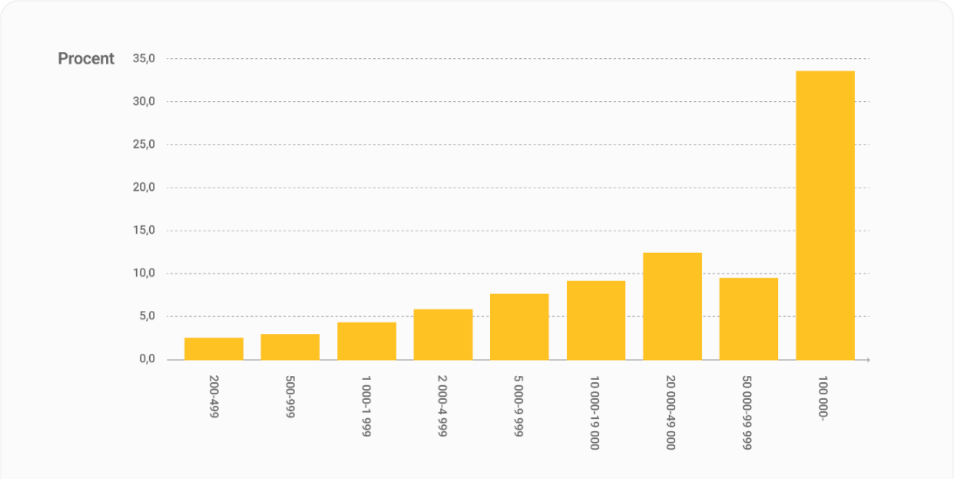

Figure 3-D: Percentage of population over city size in Sweden 2020. Source: SCB

On the one hand, it is in larger cities where problems like congestion, pollution and lack of space are most significant, and it is therefore no surprise that private mobility providers are strategically directing their focus towards these markets. On the other hand, larger cities have generally the best public transportation systems and it´s expensive to have your own car, reducing the relative appeal of individual car ownership.

Medium-sized cities, in contrast, normally have fewer issues concerning congestion and pollution, and car ownership is relatively convenient for those that can afford a car and are capable of driving. Public transport is generally satisfactory, albeit not as extensive as in larger cities, especially outside peak-hours. Depending on one's location within these cities, distances may be manageable for walking, cycling, and micro-mobility, but for some, commuting to work, school, or leisure activities still involves considerable distances and may be hard to accomplish without a car.

In smaller communities or in rural areas, public transport coverage is generally poor and accessibility[5] is low. The private car, for those who have a driver´s license and can afford a car, is a relatively easy way to solve all the daily mobility needs. But if we want to encourage people to live outside the cities, society needs to provide sustainable mobility solutions even for people that don’t own a car. Furthermore, congestion in cities is in most cases not caused by the city’s inhabitants, but by the people driving into or through the city from its surroundings, which is also the reason why congestion charges have become a popular tool to address congestion in many larger cities.

So, shared mobility services based on fully automated vehicles need to take a holistic approach on which use cases to solve independently or together with other transport modes, and the service needs to be implemented in a way that both solves users’ and society’s needs.

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[5] Accessibility generally defined as “opportunities to participate in societal life by overcoming obstacles (e.g. distance)”. Tillgänglighet – teori och praktik (trafa.se)

3.3 Roles and service concepts

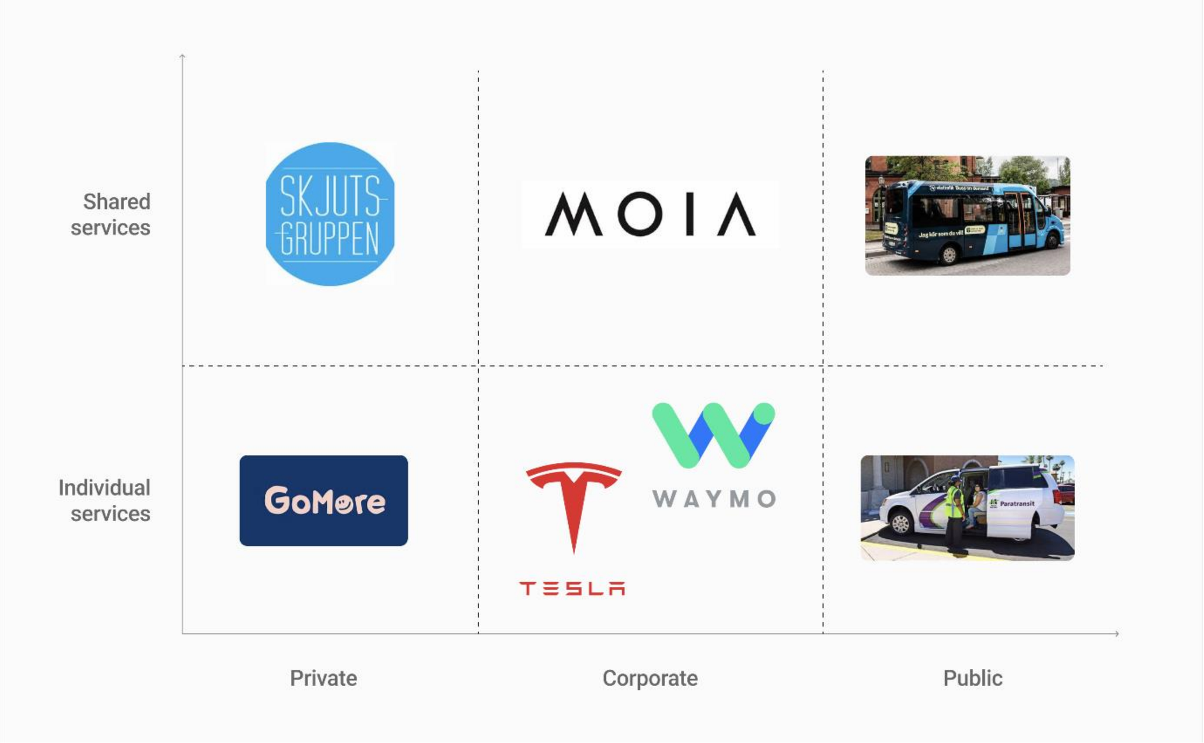

Figure 3-E: Service concept and business owner for autonomous services. Source: Mobility as a Service AB

The mobility service market can be subdivided according to many different parameters. Two parameters that are well-suited for classifying the diverse actors and roles are, on the one hand, the type of entity that owns/provides the service (private, corporate or public) and on the other hand, the service's focus on individual vs. shared usage. Focus on individual usage refers to a service with generally one passenger or multiple passengers that know each other like a family or group of friends, whereas shared services transport multiple people that are strangers to each other in the same vehicle.

Private – Individual: Today, this is a typical peer-to-peer service in which a private person rents out their car to a private customer for individual usage.

Private – Shared: a service belongs to this category if a private person drives to a destination and provides a ride-pooling service by picking up other private customers that intend to go to the same destination.

Both categories described above are today niche applications and often impractical when applied to conventional passenger cars but could merge and become more attractive when autonomy is added to the mix. In theory, a wider adaption could lead to a slight reduction in overall vehicles, but there are few coordination benefits with other public transportation systems, and ridesharing will probably be limited as long as the vehicles aren't designed and optimized for that purpose.

Corporate – Individual: This category includes two types of services – Firstly, traditional taxi service offered by taxi companies directly or on platforms like Uber and Lyft. There is no ride sharing with strangers, only individual customers (or at best people that know each other sharing a ride). If provided by an AV the authors refer to this type of service as “robotaxi”. Since the service is offered by commercial actors, some kind of dynamic pricing can be assumed which might lead to increased inequality with a lot more vehicles being dispatched to richer areas and poorer areas being neglected. And even in the (unlikely) scenario where robotaxi rides become so cheap that there can be an abundance of vehicles that offer affordable mobility to everyone there’s still the issue of added congestion and more vehicles on the roads if the robotaxi mainly offer individual rides, (similar to the “Private-Individual” scenario described above). Secondly, private companies offering automated driving functionality to their car customers, e.g. Tesla providing what they call "Full Self-Driving” capability as an add-on service. The naming is of course misleading, since it sounds like Level 5 autonomy while, in the authors’ opinion, it is quite clearly only a Level 2 system[6]. We believe that it will take a very long time to get anywhere near Level 5. And even if this kind of service would be available as a Level 4 service in a large enough area for customers to be attractive, private cars would drive around not only with their owners in them but also empty, which would ultimately increase vehicle kilometers, congestion and land use of road infrastructure (the average occupancy of passenger cars in Europe is 1.2-1.5 and that average would go down even further if vehicles also drive empty).

Corporate – Shared: A good example of this kind of service is MOIA, a mobility service that offers shared rides to private and corporate customers, but also integrates with public transport and with subsidized rides. In theory, regulations could dictate that only shared rides are provided or impose an obligation to provide rides to everyone within a certain geographic area to reduce the need for private cars and, overall, fewer vehicles. However, it is unclear how and under what legal framework this can be regulated. Currently, there are no such conditions tied to taxi permits or AD permits. A comparison could be made to regulation around electric scooters: After somewhat chaotic initial roll-outs cities like e.g. Gothenburg have gone over to allocating licenses for a defined number of vehicles under the Public Order Act.

Public – Individual: Today, public transport authorities and cities/municipalities already offer individual paratransit, medical- and school trips on an on-demand basis. These are not, by definition, individual mobility services, i.e. rides might be shared if multiple passengers have similar mobility demands (e.g. in the case of school taxis) but often the rides are conducted individually simply because there are no other customers nearby at the same time. Being a public service, pricing is set to be affordable for everyone that is eligible to use the service (i.e. it decreases mobility related inequality), but that usually means that ticket revenues don’t cover the direct costs of the service.

Public - Shared: This includes regular line based- and on-demand public transport. Public product ownership means a public entity (usually the PTA) is the owner/provider of the service, procuring the solution by means of a public tender, and integrating and coordinating it with other public transportation modes. It involves coordination of product offerings and pricing, where trips are potentially subsidized. As long as vehicles operate on fixed routes and timetables, AD technology would only help to fix driver shortages and reduce costs in general, but the customer experience would largely remain unchanged. The much larger potential lays in using AVs to enhance public transport by adding (shared) on-demand services on a large scale.

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[6] For a detailed description of the different SAE levels of driving automation, please refer to SAE Levels of Driving Automation™ Refined for Clarity and International Audience

Combinations: The matrix is a way of categorizing roles and service concepts, but the reality isn't that simple. There are several examples of "hybrids" or services that are somewhere between categories, for example Lynk&Co that focuses on individual usage, but it can be discussed if the owner/provider of the service is private or corporate. Or Tesla's vision of turning your private car into a robotaxi as soon as "full self driving" would eventually be available. Other examples would be MOIA accepting public transport trips for specific customer segments (i.e. the service moves from "corporate" to "public") and getting paid from the public side or Uber Transit and conventional taxi companies that operate on behalf of public transportation at some times and offer trips through their own platform to end customers at other times. In Sweden, private taxi services would not survive outside major cities without publicly paid trips - 50 percentage of the revenues for taxi companies come from the public sector[7].

In general, it can be assumed that the dawn of AD technology will change the traditional market categories.

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[7] taxibranschlaget2021final.pdf (taxiforbundet.se)

3.4 Geographic differences

The AV landscape varies drastically across regions, and it is often said that Europe lags behind China and the US in the race towards deploying autonomous vehicles at scale. This assessment is often based on the technical maturity of the service provided to customers and the number of AVs on public roads, which lead to significant differences in (perceived) AV maturity in the different regions. However, an assessment of the progress towards deployment at scale also needs to consider differences in maturity of regulations, policies, and public opinion around AVs. Maturity of regulation reflects transparency and efficiency of the permitting process, and the maturity of AD related policies depends on how well the deployment of a complex technology like AD at scale is anchored in public opinion and political decision making. If seen from the point of view of an AD company or investor: The more mature regulations and policies are, the smaller the risks from changes in regulation, politics, and/or public opinion.

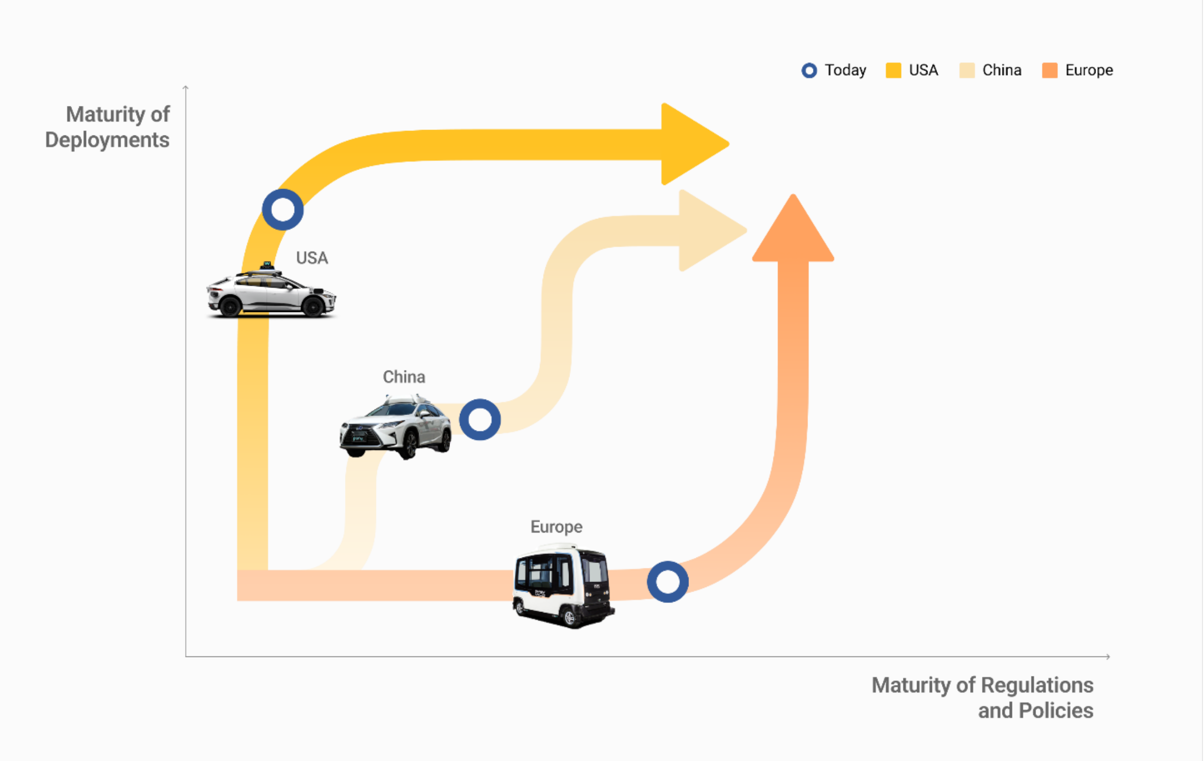

Figure 3-F: progress towards large scale roll-out of AVs and the different approaches in the three major AV markets. Source: Mobility as a Service AB

In the **US**, the market on which most media attention is focused, the permitting process leans heavily on self-certification, allowing companies to deploy (in some states) without proving safety transparently to an authority beforehand. This has led to quite large AV fleets providing services with high technical maturity, most notably Waymo (and Cruise until their permit was retracted) providing robotaxi services (i.e. single rides without ride sharing) without an on-board safety-driver to paying customers in large parts of e.g. San Francisco and Phoenix. So far, only retrofitted passenger cars have been used, but tests of purpose-built vehicles are planned during 2024. At the same time, deployment areas are growing, and fleets are deployed in additional states. There are some collaboration projects with public transport, but those are mainly initiated and driven by private actors (May Mobility, Uber Transit, Waymo in Phoenix[8]) and there's comparably little public or political discussion or planning of how mobility services based on AVs should be designed to serve the common good rather than only creating value for the individual user. Although the maturity of deployments is high, the maturity of regulations and policies is comparably low in the US and the disadvantages of this reactive "after the crash"-regulation approach and lack of centralized public planning can be clearly witnessed in the case of Cruise's accident in October 2023 that led not only to Californian authorities withdrawing Cruise's permission but also to a huge general backlash in public opinion against AVs on public roads. Furthermore, legislation in general is quite decentralized in the US, which means there are currently no federal regulations around AVs. States have a lot of regulatory independence, which adds to the regulatory uncertainty that might turn out to be a big hindrance to further market growth.

Europe has in general a more predictable approach to AD regulation with uniform rules, procedures and processes for type approval and based on those EU regulations, many member states are drafting their own specific legislation and policies for AVs. Individual cities and regions create policies for shared AD mobility to become a part of public transport. For example, Swedish legislation on trial operations with AVs was introduced in 2017 and Sweden has begun to re-write the legislation for a wider adaptation of AD[9].

In Europe, there have been a lot of pilot deployment with comparably low maturity (low speed, fixed route, on-board safety driver), that involve shuttle busses from companies like Easyride and Navya, often financed publicly, and in collaboration with public transport. But, mainly due to the much stricter requirements to prove very high levels of safety before putting AVs on the road, there are no big scale deployments or deployments without a safety driver in Europe yet. But while the maturity of deployments is low, the high maturity of regulations & policies can become a large advantage since it drastically reduces uncertainty and long-term risks, a factor that might be valued even higher by investors and AD companies in the face of the recent public backlash against AVs in the US. There are multiple interesting developments in Europe when it comes to both new purpose-built AD micro busses (e.g. the Vision M developed by Zeekr Tech Europe) - and shuttle busses (e.g. the Holon Mover, or the AD shuttle cooperations of VDL/Schaeffler[10] and eVersum/ZF[11]) as well as larger AD busses. Additionally, PTAs in larger cities have started ambitious programs to roll-out large fleets of purpose-built AVs as part of the cities' public transport systems (most notably, Oslo and Hamburg).

In Asia most focus is on **China** with deployments of both robotaxi services and public transport type shuttle bus services, but a lot of progress is also made in in Japan, Singapore, and South Korea. Companies like WeRide, Baidu and Pony.ai (that is partly a US company) are in the forefront with a high technical maturity and deployments at scale both when it comes to number of vehicles and size of deployment areas.

Somewhat simplified, China's approach can be described as a mix of or middle ground between the US and European approaches. Chinas path towards a large-scale AV roll-out was initially more like the US with less regulated, high maturity deployments of large robotaxi fleets while later there was a shift more towards the European approach of stricter

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[8] Cities | May Mobility, Expand Your Transit Services | Uber Transit, Partnering with Valley Metro to explore public transportation solutions | by Waymo Team | Waymo | Medium

[9] SOU 2018:16 and Ds 2021:28

[10] Schaeffler and VDL Groep to team up on self-driving shuttles | Schaeffler Nordic (mynewsdesk.com)

[11] eVersum and ZF deliver their inaugural AD-enabled eVersum eShuttle (sustainable-bus.com)

(centralized) regulation. In December 2023, China’s first regulation on commercial operation of autonomous vehicles went into effect. It sets some ground rules for different kinds of vehicles: “Roboshuttles” and “robotrucks” are required to have on-board safety operators, while “robotaxis” can use remote operators (however, the ratio of robotaxis to remote operators cannot exceed 3:1) and there are rules specifying what data companies need to report in case of an accident.

In the shift from combustion engine- to electric vehicles, Asian OEMs have proven their ability to quickly achieve high market shares when a technological shift offered an opportunity. It can be expected that, as soon as technology and legal frameworks are ready, Chinese companies will again be quick to adapt and ramp up towards large-scale production.

So, in the race towards deploying autonomous vehicles at scale, it is far too early to declare any region to be the “winner” and it’s doubtful if seeing it as a race that can be won even is the right interpretation. On the contrary, every region’s approach has its advantages and disadvantages and if the advantages of one region’s approach can help the others to overcome their own approaches’ disadvantages this leads to mutual benefits.

4 Ecosystem

This chapter describes the eco-system of shared services based on automated on-road vehicles by describing the core components needed to provide a holistic service; Vehicle, AD-system, Service- and Operations. Secondly it touches upon the frameworks that effect the market space directly and indirectly.

Furthermore, the chapter also includes a description of some of the most relevant initiatives and actors on the market today.

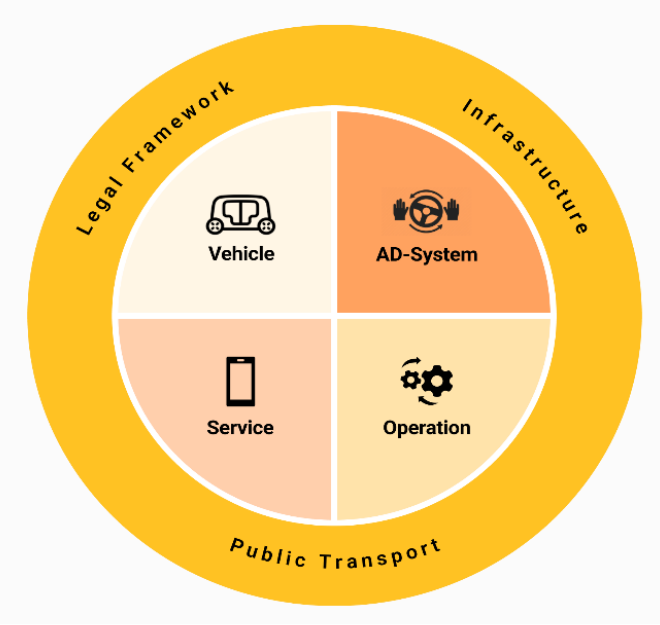

Figure 4-A: Eco system for shared autonomous vehicles. Source: Mobility as a Service AB.

4.1 Vehicle

While the full potential of AD technology hinges on its deployment within a shared mobility service and it is therefore crucial to employ a more holistic approach to the overall eco-system, the vehicle itself remains the core element of the service. In general, a fully automated on-road vehicle can be anything from a compact one-seater (or even smaller, considering applications like package or food delivery) to retrofitted passenger cars, shuttle busses and large articulated city buses accommodating a hundred or more passengers. However, as described in Section “Clarification and limitation of scope”, the authors believe, that medium-sized shared vehicles with four to approximately 16 seats possess the greatest potential to transform the mobility sector as they enable a service that can combine the transport efficiency of conventional public transport with the individual flexibility required to compete with the privately owned car.

Various terms exist for these purpose-built shared AD Level 4 vehicles, and in this report, we'll refer to "AD micro buses" (4-8 seats) for the smaller range and "AD shuttles" (9-16 seats) for the larger end of the seat spectrum.

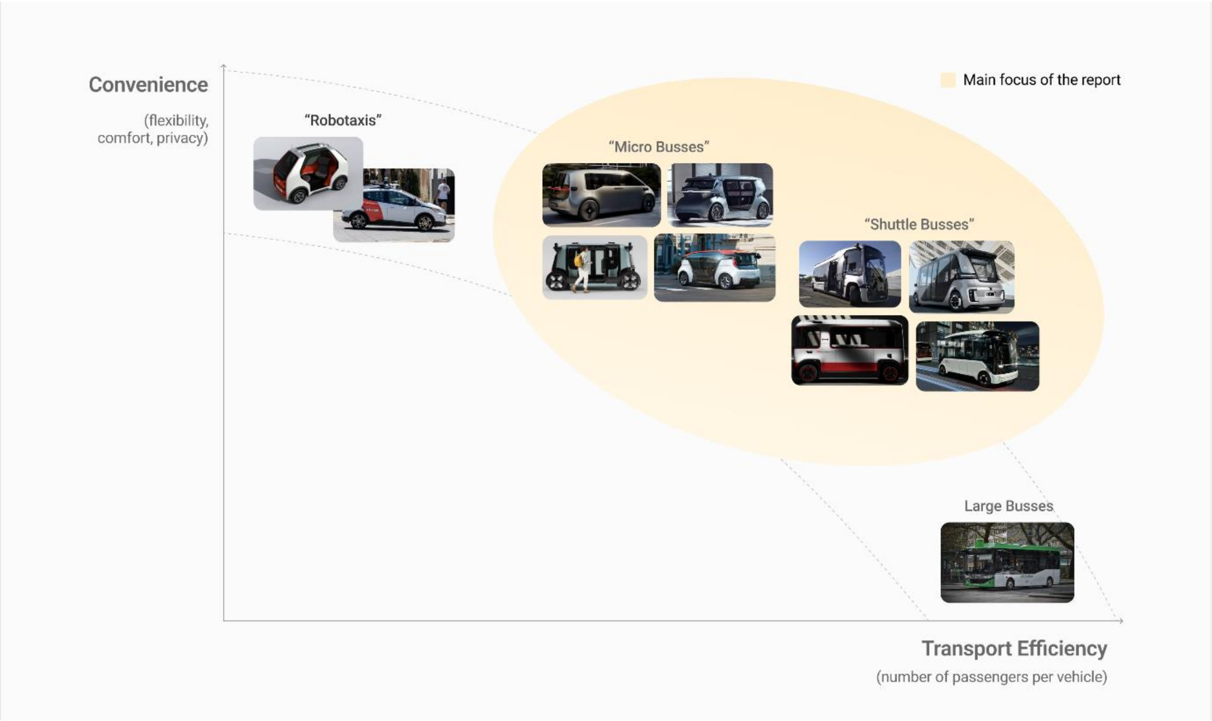

Figure 4-B: Different types of AD vehicles for transporting people. Source: Mobility as a Service AB

Fixed route, low speed demonstrators

During the past ten or so years, there have been numerous pilots around the globe with demonstration vehicles developed or sourced by companies like Navya, Easymile, Local Motors etc. These demo pilots have had their purpose of demonstrating self-driving capability, testing legislation and policy process, getting valuable feedback from customers as well as testing collaboration between private and public entities. However, because of, amongst others, limitation in speed, reliability, and self-driving capability they have not really fulfilled a mobility need. The vehicles have their limitation and quality challenges in basic functionality like heating, ventilation, door opening, suspensions and vehicle motion, but also in the AD hardware and data capacity. There have been initiatives to retrofit these vehicles with functional safety compliant drive-by-wire ("DbW") but the authors consider this generation of vehicles to be more like a dead end than a way forward towards large scale deployment. And in some cases, the fact that these early, low-maturity deployments have shaped the public opinion on the capability and potential of AVs has become an additional obstacle in discussions with potential investors and decision makers.

Figure 4-C. Source Emma Lund, Trivector

Specific vehicle properties & requirements due to Level 4 autonomy

Since the vehicle is not intended to be driven manually, the most obvious difference to a conventional passenger car or bus is the lack of a steering wheel and pedals. This leads to plenty of new ways to shape the vehicle's interior, many Lv4/5[12] AV concepts and prototypes feature for example a rearward facing first row of seats where the steering wheel and pedals would otherwise be in a conventional car.

Figure 4-D: Seating layouts featuring rearward facing front row seats in Zeekr M-Vision (left), Zoox (middle), and Cruise Origin (right)

But the even larger implications for the vehicle design are not visible from outside and therefore maybe not as obvious to the broader public: In Europe, approval of an AV that operates without a safety driver generally requires a fully redundant DbW system, i.e. replacing the mechanical/hydraulic inputs from the steering column and brake pedals with electronically controlled actuators that receive the corresponding signals from the AD system (for a more detailed discussion of the challenges around DbW, please refer to 5.2).

Vehicle properties due to ridesharing & fleet operation

Apart from the mainly AD related properties described above, there are a lot of design requirements and properties of purpose-built AVs that differ dramatically from conventional passenger cars, due to the vehicles being part of a larger fleet that provide a ride-sharing service.

Ingress & egress: While the time it takes to enter and leave the vehicle is less important for a private car, it becomes very important in a shared vehicle in which the (perceived) smoothness of the service is strongly dependent on the extra time it takes to pick up and drop off passengers (both the customer her-/himself and even more importantly, additional passengers when the customer already sits in the vehicle). Therefore, the doors need to be considerably larger to facilitate a quick and comfortable ingress and egress, they should open and close automatically and should take as little space on the sidewalk as possible during opening and closing. Furthermore, the vehicle design needs to consider a wider range of users when it comes to aspects like age, body sizes and physical or mental disabilities and aspects like (amongst many others) stepping height, headroom, visual contrasts, and sound design need careful consideration.

Seats/passenger environment: The share of shorter trips in a shared mobility service that is integrated with public transport is higher than when using a passenger car for the whole journey and therefore, the seats need to be optimized for sitting shorter durations. User studies at NEVS have shown that the seating position needs to be higher, more like in a

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[12] For a detailed description of the different SAE levels of driving automation, please refer to SAE Levels of Driving Automation™ Refined for Clarity and International Audience

public bus to be considered comfortable under these circumstances. Another requirement of shared AVs that needs to be considered for the seats and the overall interior is the much bigger importance of durability and cleanability as these directly influence uptime and fleet utilization. Furthermore, customer needs like stowing (hand-) luggage, charging electronical devices or individual passenger information need to be included in every individual seat or its direct surroundings and not only as a vehicle level requirement.

Battery capacity: an aspect of the vehicle specifications with great potential for optimization is battery capacity. In a privately owned car, the required/preferred battery capacity is often based on the range required for the longest journey that the customer needs to be able to drive on a regular basis without a longer stop for charging (e.g. a return trip to and from work plus some safety margin for unforeseen de-tours or exceptionally high heating/cooling demand) or is simply determined via benchmarking of different EV competitors. The “worst-case” scenario for the private EV owner is a longer charging stop during a time critical journey. In the case of a fleet of shared electrical AVs, the customer provides the intended destination when booking in the app and the fleet orchestration system takes the required state of charge into account when choosing the right vehicle for the trip. Furthermore, even if a vehicle’s battery capacity turns out to be insufficient to complete a customer trip, the customer’s worst-case scenario is having to switch to a different vehicle of the fleet to complete the trip. However, with larger doors opening and closing more frequently requiring extra heating or cooling on cold and hot days respectively and additional energy consumption of AD hardware components a larger part of the battery capacity needs to be allocated to non-driving related tasks. The optimal energy consumption is the result of a fleet level optimization and is strongly dependent on the operational area and intended usage, but in general it can be said that the required battery capacity tends to be lower than for private EVs.

4.2 Automated Driving System (ADS)

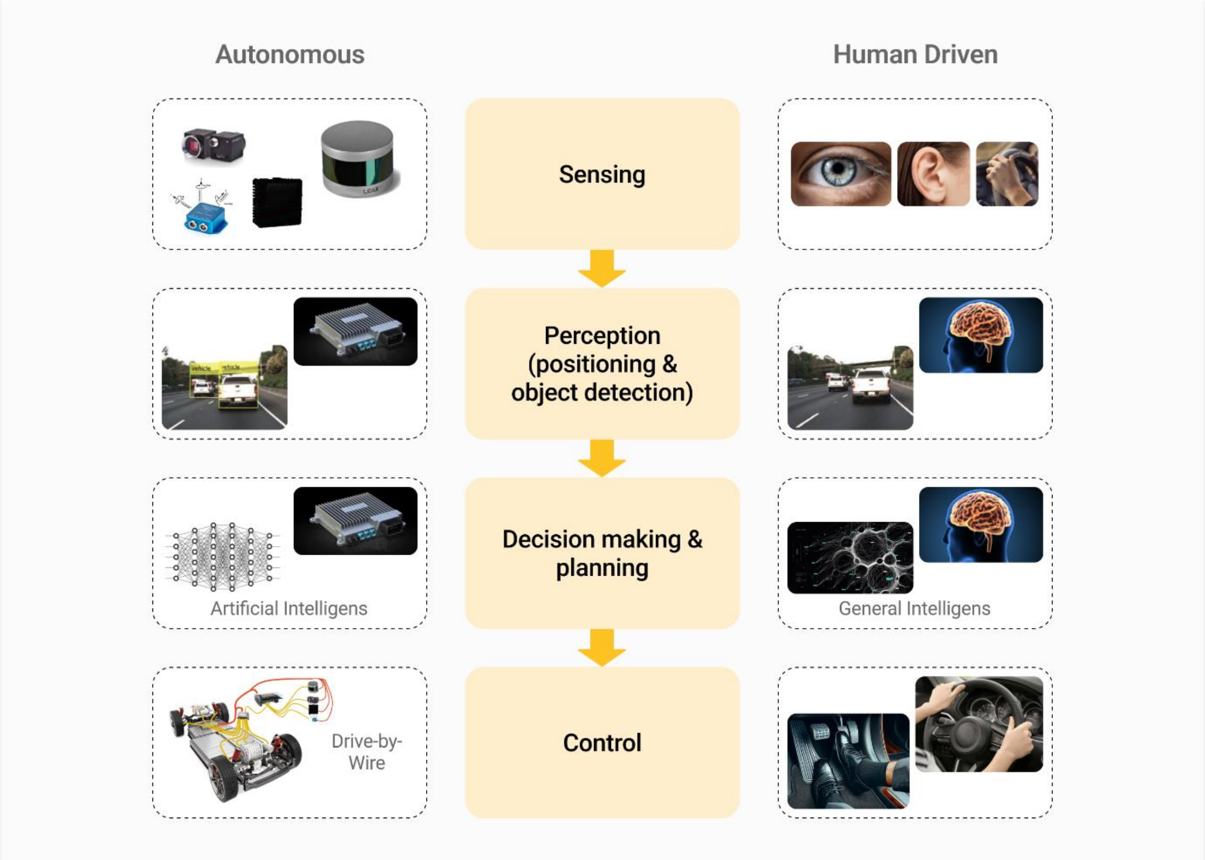

Figure 4-E: Overview of the different subsystems of the AD system and their equivalents in a human driven vehicle. Source: Mobility as a Service Ab.

In General, the ADS can be divided into four main subsystems: sensing, perception, decision making/planning, and control.

Although technically complex, the sensing and perception part are comparably intuitive: A set of sensors (in most cases cameras, lidars and radars) provide the AD software with a real-time 3D image of the vehicle’s surrounding and the perception module of the AD software “understands” the surrounding by identifying and classifying (moving and static) objects and the vehicle’s position in the world by referencing a high-definition map of the area. Compared to a human driver, those systems perform the tasks of the driver’s eyes and visual cortex in the driver’s brain.

The subsystem that is probably discussed the most in the media and around which there seems to be the most controversy and misunderstandings is decision-making & planning. The decision-making module processes the information it receives from the perception module and performs the equivalent of what would be considered, in a human driver, the willful/deliberate part of the driving task (i.e. the decision of how and where to drive); a function that is not only technically complex but has also large ethical and legal implications that need to be understood and addressed in a way that satisfies not only technical experts but also the general public.

There are two general development methods that are relevant for the decision-making module of the AD software: Firstly, the more traditional rule-based programming (i.e. what can be simplistically described as “if a, then b” type of rules/logic provided by a human programmer) and secondly, machine learning methods. Machine learning systems examine large amounts of recorded data (i.e. traffic scenarios and the corresponding driving decisions) and make decisions based on patterns that the system detects in that data. It can be “trained” to behave as it should with huge amounts of recorded real-world driving data and even more simulated driving scenarios providing the system with the flexibility to handle situations that are similar (but not equal) to situations it has already encountered in training. Another advantage of machine learning methods is the flexibility to adapt to new kinds of situations and to automatically evolve and improve the system’s capabilities over time with new data from new scenarios.

Most AD systems today are based on a combination of machine learning and rule-based programming[13] where the latter provides some predictability and makes machine learning more efficient (please refer to chapters 5.3 and 5.6 for a more detailed discussion of the challenges arising from this combination of approaches).

The last subsystem is the control module, i.e. the AD system’s interface to the vehicle’s steering, acceleration, and braking functions that replaces the steering wheel and foot pedals operated by the human driver. Most AD companies currently employ retrofitted passenger cars for their on-road testing (in the US even for commercial services) in which the AD system often uses actuators that were originally intended to support the driver as a stand-alone system to perform the complete driving task. This approach offers of course the huge advantage, that the base vehicle is already type approved, allowing the AD company to focus solely on perfecting the AD system. However, while effective in the short term, relying on retrofitted cars poses potential mid- and long-term challenges. The need for direct communication between the AD system and the vehicle's steering, braking, and acceleration systems through interfaces not originally intended for this purpose is certainly a huge hinder when applying for permit for driverless operation in Europe (please refer to 5.2 for more on this topic). In a purpose-built AV, a unified vehicle motion interface provided by the vehicle manufacturer becomes paramount. This not only simplifies technical integration but, more crucially, establishes a clear division of responsibility between the AD company and the vehicle manufacturer as a possible error can be allocated to either the AD software sending the wrong command or the vehicle not performing the AD software’s command correctly.

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[13] For an interesting approach of how the “black box” properties of machine learning systems could be mitigated, please refer to Engström, Wei, et. al. (2024) “Resolving uncertainty on the fly: modeling adaptive driving behavior as active inference”.

4.3 Service & Operations

Creating a functional service involves a complex integration of various systems and processes, often from different stakeholders. This "system of systems" is not fully established today. It will evolve over time, and it is reasonable to assume that no single actor will excel in every aspect of it. Instead, it needs to be a collaboration of multiple stakeholders specializing in different aspects (please refer to the image below for an overview of the systems and sub-systems).

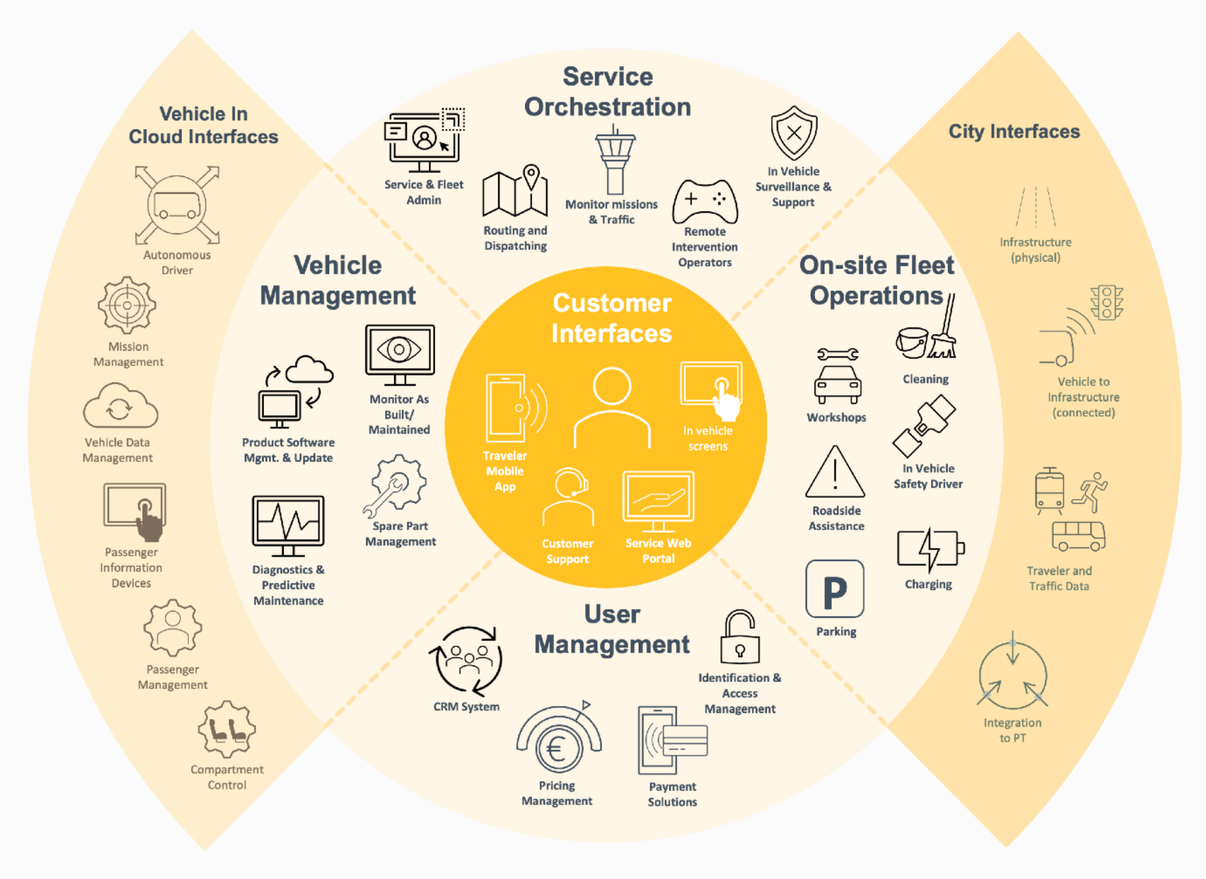

Figure 4-F: Overview of the systems and sub-systems involved in the overall service. Source: Mobility as a Service AB.

Customer interfaces: That's the service's interface to the customer before, during, and after the journey. It can be handled through a mobile app, external- and internal vehicle screens, sound and voice in or around the vehicle, etc. For a positive customer experience throughout the journey, efficient communication between the service and the vehicle is paramount which also needs to be considered during requirements specification and early in the vehicle development process. Examples of novel features due to the vehicle providing a service instead of being a privately owned consumer product include quick/automated passenger identification, individual information through in-vehicle screens, communication with traffic control or customer support, and handling of emergency stop requests.

Vehicle management: The main task of any vehicle management system is to optimize vehicle uptime and to ensure that there are always enough operational vehicles available to provide an acceptable service level to all its customers. This is done by capturing data from the vehicle and all its components and ensuring that the vehicle is maintained and repaired in a timely manner. It also includes updating software at appropriate times (while not disrupting service operation). Since there is no driver to detect potential issues, it is even more important that all components of the vehicle are equipped with sensors, and there are systems to automatically monitor these sensors. This is a collaboration between vehicle manufacturers and operators, with the vehicle manufacturer being responsible for the long-term functionality of the vehicle in terms of both hardware and software. However, some parts can be practically handled by the operator, and regardless of responsibility allocation, coordination of software updates, maintenance, and hardware replacement is needed.

Service orchestration: Service Orchestration includes ensuring that the right vehicle gets the right assignment, monitoring traffic, performing remote operations, and providing (in-vehicle) support to customers. The most central part of the service and crucial for efficiency and profitability is the ability to automatically send the right vehicle on the right assignment, via the right route. For this aspect, there are several specialized companies such as VIA, Padam, ioki, Uber, and Moia. This is also an integrated part of the service where the back-end system needs to communicate with the vehicle's AD system. Although this aspect is mainly automated, manual monitoring is needed, and it is reasonable to assume that traffic management staff is responsible for both service monitoring and remote intervention operations to minimize personnel costs. Traditionally, this part is handled by the operator, but for fully automated vehicles, it may initially involve the AD system provider and possibly the vehicle manufacturer.

On-site Fleet Operations: This includes the mainly practical aspects of daily operations - ensuring that vehicles and personnel are ready for service and handling incidents. This also includes facilities such as depots and charging infrastructure. Workshops are linked to vehicle management, where minor maintenance can be handled at the depot and more extensive repairs can be performed by specialized workshops or directly by the vehicle manufacturer. Initially, it may probably be wise for the vehicle manufacturer to have personnel that handles as much as possible on-site until a certain level of product maturity is achieved.

User management: Includes underlying systems for identification, pricing, payment, customer relation management (CRM), etc. These are often existing systems that use standardized APIs for integration. If there are requirements for identification other than "blipping" a ticket or a booking, solutions that need to be integrated with both the hardware- and software level of the vehicle and underlying systems. For public transport, validation of ticket, with no human on-board, will be a potential challenge.

Vehicle interfaces: The representation of this aspect in *Figure 4-F* refers to a cloud based digital twin of the vehicle that acts as an interface between the service's back-end systems and the physical vehicle, including the AD system. To minimize cyber security risks, this can be the single access point for communication to and from the vehicle (but there are of course also other approaches). Another aspect is the interaction between Routing & Dispatching and the vehicle's AD system. To optimize fleet efficiency the Routing & Dispatching system needs be able to continuously route and re-route vehicles via this interface.

City integration: Refers to integrations with external systems such as external fixed data about infrastructure (maps), or real time information like traffic lights and digital traffic rules.

4.4 Public transport

In cities across Europe, public transport systems like buses, trams, subways, and trains are commonly used by residents for daily commuting as well as for intercity travel. The concept of public transport, as defined by EU Regulation 1370/2007, encompasses passenger transport of general economic interest, consistently offered to the public without discrimination. Traditionally, this includes mostly fixed-schedule services like trains, subways, trams, buses, and boats, each adhering to predetermined routes. In Sweden buses stand for 85% of the total supply[14]. Public transport tends to have a higher market share in the EU compared to the US. This is due to several reasons, including denser urban populations, more extensive public transportation networks, higher fuel prices, and often more favorable policies and investments in public transit infrastructure.

However, the landscape is evolving, with the emergence of Demand-Responsive Transport (DRT) for public usage but also paratransit services catering to individuals with disabilities or mobility challenges. DRT, synonymous with on-demand services, has been perceived as having limitations and not serving as a comprehensive public alternative due to high costs per journey. Nevertheless, during recent years, perception of DRT services has started to change across Europe.

The legal structures and organization of public transport varies across Europe, with responsibilities shared among communities, regions, and nations. The level of regulation also differs, with Sweden representing a fully deregulated market. In Sweden, 21 Public Transport Agencies (PTAs) organized as regional entities or as public companies (e.g. Västtrafik in Västra Götaland), are responsible for organizing public transport. This includes strategy, development, brand management, sales channels, customer support, timetable creation, network definition, ticketing system, pricing determination, vehicle management, and more. PTAs also procure (through public tenders) operational services from Public Transport Operators (PTOs). In Europe in general many PTOs are public entities that define their mission together with the PTA, but on de-regulated markets like Sweden many private PTO like MTR, Nobina, Transdev and Keolis, or consortia of smaller entities, handle operations. In smaller and rural areas, DRT services are often managed by taxi companies with a significant share of its revenue coming from public tenders (as described in chapter 3.3).

Irrespective of the public transport entity being a public company or an authority, they must conduct public procurement processes to select providers of public transport services, and these procurements must comply with specific national regulations. In Sweden these regulations are stipulated in LOU, LUF, and the Traffic Ordinance and similar legislation applies in the rest of Europe. Essentially, it involves not just choosing a provider above a certain threshold, but rather, services must be procured in a manner that is transparent, non-discriminatory and in open competition. However, there are ways to conduct procurements specifically for innovations where precise requirements or assessment models cannot be described. The most common procedure is that the PTA tenders an operator that is responsible for the vehicles involved, but the PTA has detailed requirements on the vehicle. In the Nordics there is a defined standard for busses that can be complemented with company specific requirements[15]. Regarding trains, trams, and boats it is more common that

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[14] Regional linjetrafik 2022 (trafa.se)
[15] Bus Nordic (svenskkollektivtrafik.se)

the PTA owns the vehicles, because of the long lifetime, while busses and cars are generally owned by the operators. In the private sector companies have in general more freedom to cooperate based on bilateral agreements or in the form of a joint venture which is challenging for public organizations due to transparency requirements and procurement regulations.

The interest in automating transport services is widespread among PTAs, varying based on the region's defined objectives. Automation represents cost-saving opportunities for bus services by eliminating the need for drivers and enabling more efficient timetables. In the case of DRT services, automation can replace inefficient fixed bus lines or provide on-demand services with improved conditions for a broader audience.

4.5 Infrastructure

Mobility related infrastructure can be divided into digital and physical infrastructure, as well as private and publicly owned infrastructure. The below image gives an overview of the aspects and systems that need to be considered when discussing infrastructure in the context of AVs:

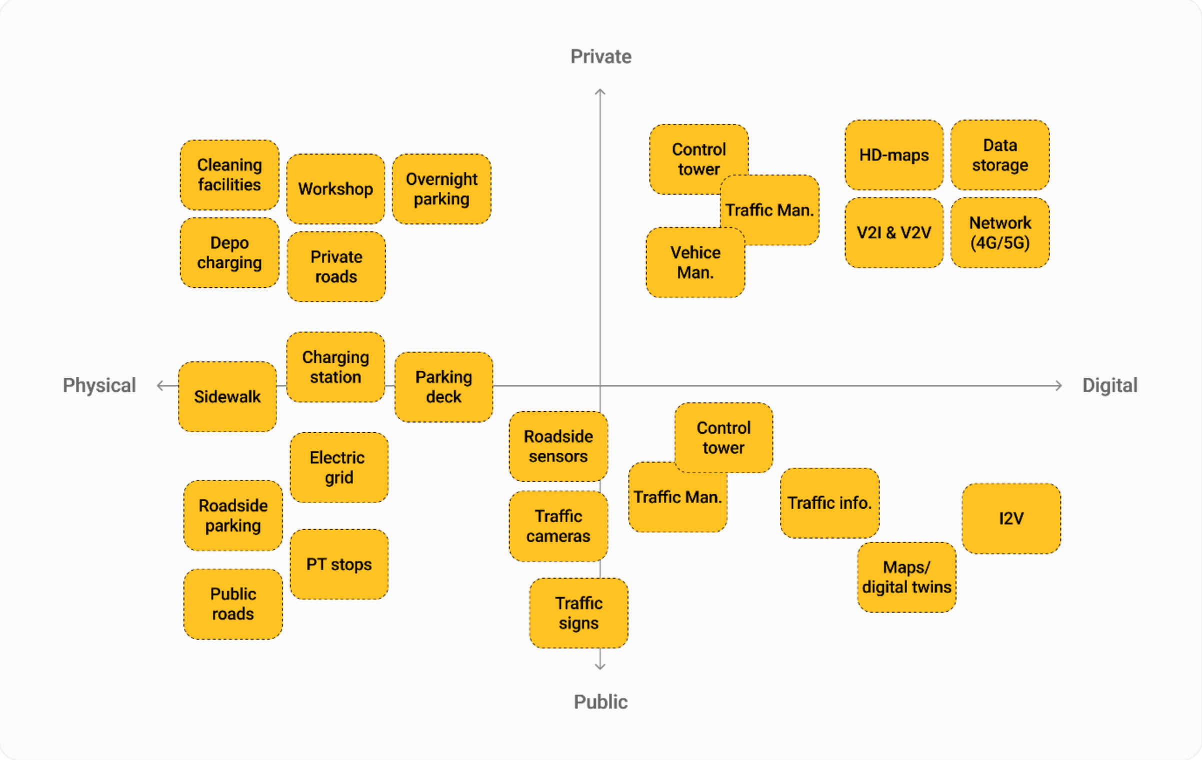

Figure 4-G: Overview of aspects of digital and physical infrastructure in public and private ownership. Source: Mobility as a Service AB with inspiration from Färdplan Autonom Mobilitet.

Many ideas have been presented over the years for new mobility solutions that involve huge infrastructure investments, like monorails, tunnels, new dedicated roads or adding lanes to existing ones. One of the fundamental advantages of the type of mobility services that become possible with the emergence of AD and purpose-built vehicles that are optimized for sharing is that they don't require fundamental changes in physical or digital infrastructure.

With that said, the existing infrastructural framework will probably need minor adjustments to be able to provide an efficient service. Examples of infrastructure that can be improved[16]:

- Unattended pedestrian crossings or intersections on busy roads, the AD system might have challenges “squeezing through”[17].
- Roundabouts with high traffic congestion/queues. Same reason as above.
- Poor road markings and signage (often around roadworks) need to be rectified.
- Well defined and secure Pick Up and Drop Off locations (PUDOs) to minimize risks while entering and leaving the vehicles.
- Parking areas for waiting before pick-up (initial problem, when still having the same space occupied by private cars).
- Road maintenance, including snow removal and trimming overhanging trees and bushes.

There’s plenty of publicly available videos of AVs handling the kinds of situation described above very well, but since these are produced and uploaded by the AD companies themselves, there’s no way to know/prove if these videos are cherry-picked or represent “normal” AV behavior.

Depots, workshops, washing facilities, parking, and charging infrastructure will of course be required, these aspects are unlikely to become bottlenecks since as long as the new mobility services replace a larger number of passenger cars, they will free up more infrastructure than they will require. For example, existing facilities, such as parking garages of shopping malls and offices could be utilized for overnight parking of micro buss type vehicles.

Connectivity through 4G, 5G, etc., is essential but not decisive for operating vehicles, as EU legislation mandates that vehicles should be able to "take care of themselves" in uncontrolled situations. This means that Remote driving will not be a solution that can be used in high-speed operation, but it might be used in depots, garages or for parking. However, it is crucial for effective video transmission to a traffic management system and for streamlining operations.

Other connected solutions and vehicle-to-everything (V2X) communication, such as connected traffic lights, digital traffic rules, and real-time traffic supervision, can enhance operational efficiency but are not mandatory prerequisites.

Data, including passenger statistics, traffic flow, map data, and 3D data, are also crucial areas for becoming more efficient and avoiding starting each new implementation from scratch.

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[16] For a detailed analysis of infrastructure adjustments, please refer to the results of the DriveSweden project “Färdplan Autonom Mobilitet”, (2023): Roadmap for sustainable mobility solutions based on autonomous driving in a complex city environment | Drive Sweden

4.6 Legal frameworks

As mentioned in 0, the legal frameworks surrounding the deployment of AVs vary significantly between Europe, the US, and China mainly due to different regulatory approaches. The European Union tends to take a more centralized approach to regulation, with EU directives and regulations setting overarching standards that member states follow. But the member states are largely independent in how to apply these regulations in their national processes around permitting and deployment. In the US, regulation of AVs is more decentralized and state-level regulations vary significantly leading to a patchwork of regulations across the country. China has adopted a top-down approach to AV regulation, with the central government playing a prominent role in setting standards and regulations. In general, the US permitting process relies more on self-certifications whereas in Europe and China, the authorities are much more involved in assessing the safety of a technology before it's deployed on public streets.

Vehicle and technology related legal frameworks

The most important regulations for the deployment of autonomous vehicles in Europe are Implementing Regulation (EU) 2022/1426 and Regulation (EU) 2019/2144 which set detailed rules, uniform procedures, and technical specifications for the type-approval of automated driving systems in fully automated vehicles. In addition to those mainly vehicle focused regulations, other legal frameworks that are relevant to the development and deployment of AVs are product safety and -liability rules, rules on traffic insurance as well as general traffic – and driving license rules, market entry- and competition rules, taxi- and public transport regulations. An apt example of a regulatory initiative that isn't specifically written for AVs but can have big implications is the new European product liability directive 85/374/EEC that broadens the definition of a "product" considerably to also include, amongst others, stand-alone software and AI applications. For a very good in-depth summary of the most relevant regulations, regulatory initiatives and involved regulatory entities, please refer to "Steering the Future: An Overview of Current and Upcoming Regulations in Automated Driving: Version 0.5"[18].

4.7 Relevant initiatives and actors on the market

While many of the early market entries covered larger parts of the value chain, the trend of recent years is to focus more on a narrower core business and to enter into partnerships in order to be able to provide a full service. Still, it is an open market in that sense that most companies claim to be agnostic when it comes to collaboration and integrations. AD companies like Waymo and Cruise in the US., Baidu and pony.ia in China and Mobileye from Israel, together with European actors like Oxa and Waive are collaborating with different OEMs. Public transport operators like Transdev, Keolis, VY or ride-hailing or taxi companies like Uber, Bolt or Lyft are open for collaboration, and providers like VIA, Padam or ioki offer on-demand platform services.

Below, there's a short list of some of the most relevant initiatives and actors that the authors would recommend following.

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[18] https://ri.diva-portal.org/smash/get/diva2:1829974/FULLTEXT01.pdf

WAYMO

US. Based Waymo is number one when it comes to experience in AD services. They have conducted more than 700.000 customer paid journeys without a safety driver and have deployments covering large geographic areas in multiple states. Waymo's core capabilities are focused on AD. Today, they are using some 500 retrofitted Jaguar I-pace as main vehicle for deployment, but there's also a purpose-built vehicle, called M-Vision developed by Zeekr Technology, that is said to be ready for serial production soon. With focus on the US robotaxi/ride-hailing services market Waymo has collaborations with Uber for service- and user interfaces and with Transdev for operations and collaborations with public transport are planned. Waymo's safety case relies heavily on statistical comparison to human drivers and the latest milestone was adding freeways and highways to their operational domain.

poni.ai

Pony.ai was founded around 2018 in Silicon Valley. With operations in 6 major sites in the US and China, the company has become a leader in autonomous mobility. They claim to have driven ~18Mio miles on public roads in the US and China with their 500+ vehicles L4 fleet (~300 passenger vehicles and 200 trucks). Pony has key commercial partnerships across the value chain with OEMs like Toyota, GAC, SAIC, Sany, Logistic companies like Sinotrans, OnTime and wardware as well as hardware/sensor providers like NVIDIA, Luminar and Robosense. Pony recently announced a collaboration with Luxembourg as a first step into the European market.

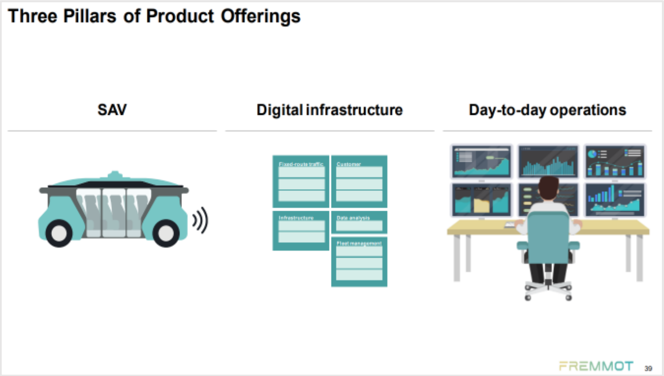
Cruise

Cruise's experience in AD combined with GM's automotive know-how and ability to develop and build vehicles on a large scale make them an important player. But following a series of incidents in San Francisco, Cruise's AD permit in California has been revoked and they have downsized their organization. Their purpose-built micro bus, the Origin, is not far from serial production readiness, but hasn't been used for transporting (paying) customers yet.

MOIA, Mobileye, VW & Holon

MOIA's extensive experience in offering on-demand services, combined with Mobileye's AD technology integrated into the VW ID Buzz vehicle and their planned purpose-built vehicle, is an interesting combination and probably the leading one in Europe. Also, Holon, which is developing a purpose-built AD shuttle, is part of this collaboration in Hamburg alongside public transportation and the PTO Hochbahn.

Fremmot



Three Pillars of Product Offerings

SAV	Digital infrastructure	Day-to-day operations

FREMMOT 39

Fremmot is Ruter's initiative to gather actors within the public sector in Europe and potentially tender and offer services fit for public transport. It is currently not communicated how the offer will be assembled and with which suppliers. Most likely, it will involve some of the above-mentioned companies. Fremmot has strong political support and letters of intent from several cities and regions across Europe. Ruter is presently conducting a pilot in Groruddalen within the EU funded program ULTIMO, with Mobileye as AD company and with retrofitted vehicles from the Chinese OEM Nio.

5 Key challenges and solutions

Replacing the private car as the main means of transportation has huge potential to reduce emissions and generally improve quality of life not only in cities but also in more rural areas. However, there are also a lot of key challenges that need to be overcome first. The chapter gives an overview of the most important technical, commercial and organizational challenges that cause the slower than expected roll-out of (purpose-built) AVs. Apart from all these individual challenges, the authors believe that another important difficulty lays in the overall (eco-)system complexity that leads to many cross-dependencies between otherwise unrelated areas that experts and organizations that focus exclusively on their area of expertise are not aware of.

It is therefore the ambition of the following chapter to give an overview of what the authors consider the most important challenges and describe those challenges to a level of detail that is relevant for anyone who is not an expert in that specific area (but who’s work in their own area of expertise might benefit from a better understanding of other areas and possible cross-dependencies).

5.1 Vehicle hardware

For people to be willing to use a shared mobility service instead of a private car, the AV needs to be purpose-built and optimized for the use cases outlined in 3.2. Already the development process of a conventional serial production passenger car is extremely complex, and a lot could be written about the challenges of conventional car (hardware) development in general. But since these processes are comparably well understood and controlled by any automotive OEM (due to long experience and optimization), this chapter will focus on the challenges specifically related to the hardware design of shared AVs.

Requirements & specifications for a purpose-built vehicle

Although there are many different naming conventions for the different steps, most OEMs would agree, that the vehicle development process follows the general logic of the so-called V-model. The concept, requirement and specification phases form the left “arm” of the V and the testing, verification, validation and finally operation of the system or product form the right “arm”.

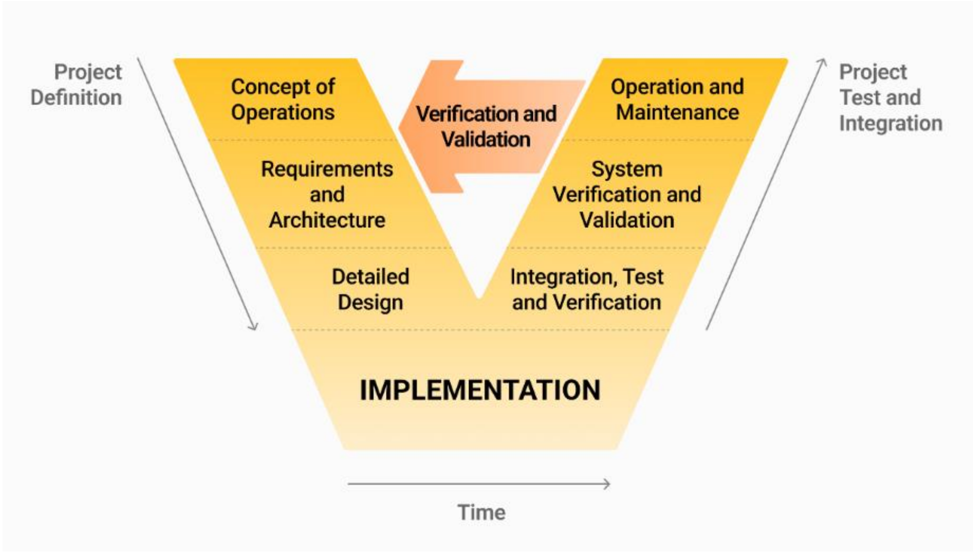


Figure 5-A: A general visualization of the V-Model (source: Wikipedia)

Especially in hardware development, the time between setting specifications and requirements and a usable prototype that can be tested internally or by end-users to get user feedback can be extremely long and costly. That means that in the development cycle of conventional vehicles, improvements or optimizations of the final product can't be fed back directly into the requirements/specification phase (as would often be possible in pure software development) but are incorporated in the requirements & specifications of a model update or the next model. In general, it can be said that the whole project definition process in automotive is extremely dependent on the collective experience of the involved engineers and developers as well as benchmarking against competitors. As long as this process is applied to developing a product that is comparable to already existing products and there's experience from using similar products in a known market, it works like a well-tuned machine and delivers extremely reliable results. The levels of reliability, safety, quality and efficiency that have been achieved in serial production passenger cars through optimization driven by fierce competition during the last 100 years of automotive development would probably be considered unachievable, if we weren't used to it from our everyday experience.

But when automotive OEMs try to apply those same processes and procedures to developing a completely new product for a service that doesn't exist yet (and therefore no-one has actual real-world experience), these detailed processes and the different departments' rigid roles in it turn out to be a huge liability instead of an enabler of a smooth development process.

An area where the shortcomings of relying on personal experience of the OEM's designers, developers and engineers in the still male dominated automotive industry become visible is the question of women's design preferences in general and women's security in particular. Many of the existing concepts for shared automated micro busses have two rows of seats facing each other (please refer to Figure 4-D for the most prominent examples). Early user studies with vehicle mock-ups at NEVS have shown that this layout is great if the passengers in the vehicle know each other (like automotive engineers sitting in a meeting to discuss the ideal layout of a shared AV) but when sharing the confined space of a small automated micro bus with strangers (and without a natural authority like a driver), many users, especially women, fell uncomfortable in this kind of seating layout.

Realistic user studies

To quickly arrive at an optimal (or at least somewhat optimal) design, realistic user feedback is required. This is true both for which functionalities / features to include in the service and vehicle and to balance possibly conflicting requirements stemming from different use cases.

Unfortunately, the results that can be obtained from purely theoretical surveys or user studies (i.e. potential users filling out questionnaires or answering theoretical questions) are of very limited value. These kinds of user studies are useful to collect (more or less) objective data like overall mobility needs and travel patterns as well as subjective opinions in relation to existing modes of transportation like e.g. private cars, busses, trains, and airplanes. But any user study concerning user interaction, design preferences and the user value of a certain function or feature require the test person to be in a as realistic situation and environment as possible for the results to be valuable for the development process. Ideally, this would be achieved by small test fleets of fully functional purpose-built AVs with different specifications, designs and functionalities operating on public streets and serving the everyday mobility needs of a diverse set of paying customers. This stands however in stark contrast to the automotive development process described above, with its long development loops and that is geared towards a “big bang” release of a finished product for which production is ramped up as quickly as possible.

Since the mobility services with the largest potential of improving the status quo need to strike a balance between the transport efficiency of traditional (fixed route, timetable based) public transport and the flexibility and comfort of the privately owned car, a lot of the concept selections and design choices that lead to the final design of the vehicle are about trade-offs and compromises. Below are some examples of trade-offs between conflicting requirements that need to be considered especially during the early design phases.

Seat arrangement, Safety and Privacy

Vehicles of the micro bus type can be shared by strangers; in which case the interior should provide as much separation and privacy as possible. But when a family or a group of friends or colleagues books a vehicle, the users would like the interior to be open with as little hinderance to social interaction as possible. A face-to-face seating arrangement is great when the person you’re facing is a friend or family member but sitting face-to-face with a stranger, especially in a confined space with no-one else around can be uncomfortable. And although the seating arrangement is probably the most obvious example, even much “smaller” design choices need to be evaluated for both scenarios as well, weighing any upside for one scenario against possible downsides for the other. Furthermore, there can also be trade-offs between privacy and (crash-) safety that need to be considered since any additional divider or enclosure that provides privacy can be dangerous in a crash or can become an obstacle when passengers need to leave the vehicle in an emergency.

The larger shuttle bus type vehicles are generally optimized more towards transport efficiency sacrificing some of the privacy and comfort that the micro buss type can offer. But although there are fewer trade-offs and compromises around privacy, balancing e.g. crash safety and efficient utilization of the vehicle’s interior can be challenging. Many shuttle bus concepts that vehicle manufacturers have presented feature not only forward and rearward facing seats, but often also seats that face sideways (mostly to utilize the area around the doors better). And while this is legal, it remains to be seen how safe this arrangement is in a crash considering that seats and seatbelts offer much less protection against sideways accelerations. In absence of a specific AD vehicle classification, AD shuttle manufacturers are likely to be required to follow M2 vehicle requirements (M2 is applied to “vehicles for the carriage of passengers with more than 8 passengers and up to 5 tons”). The testing requirements for this vehicle type are generally lower than for M1[19] vehicles, e.g. there’s no pedestrian protection requirement so the front can be flat. But even if legal requirements are (currently) lower, the expectation from the general public will still be that the new vehicles are at least as safe as private cars or conventional busses. And since most public discussions today focus on the safety of the AD system, there’s a risk that conventional (passive) safety is neglected, with potentially dramatic consequences.

Figure 5-B: A Local Motors Olli vehicle after an accident that left the safety operator critically injured although it occured at very low speed

Accessibility

Accessibility is a crucial aspect of any mobility service that is integrated with public transport. Providing mobility to people that can’t drive themselves is one of the great potentials of AVs and for people with visual, hearing, or mental disabilities, this is certainly technically possible (as long as it is considered early in the development process given high enough priority).

However, transporting people in a wheelchair remains very challenging, especially in smaller vehicles or vehicles that operate at higher speeds.

The movements and accelerations that can occur and consequently the requirements of how robustly the wheelchair needs to be strapped/fixed is strongly dependent on the vehicle’s maximum speed, and to a certain extend also on the vehicle’s weight. In AD shuttle type vehicles that operate at speeds below 50 km/h solutions like those implemented in large public transport busses today, are certainly possible and although they don’t provide the same level of safety as sitting in a regular seat with a 3-point-belt it can be expected that users would deem this level of safety acceptable as it is already accepted in public transport today.

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[19] M1 applies to normal passenger cars and most likely also AD micro busses.

Transporting wheelchair users in smaller micro bus-type vehicles that operate at higher speeds requires fixing/strapping the wheelchair more robustly. The only solutions that exist today require either the help of a companion to strap the wheelchair or a somewhat standardized docking interface. Cruise have presented the currently most mature solution in a variant of their Origin vehicle with an automatic ramp and a direct docking interface that is compatible with five automatic wheelchair models.

Figure 5-C: Wheelchair integration concept in a Cruise Origin

Although this represents a huge step forward, it is highly unlikely that both the coupling between wheelchair and vehicle and the wheelchair itself could withstand the forces and strain of a crash the way a regular seat does, which would mean that the solution is potentially less safe for not only the person in the wheelchair but also the other passengers in the vehicle.

Furthermore, it needs to be considered that today, 80%[20] of the vehicles utilized in special transport services/paratransit are purpose built to a specific need and the driver often helps the passengers with a lot more than just driving the vehicle (e.g. helping the passengers to and from their home, a task that is much harder to automate than the driving itself).

Luggage

Transporting passengers with luggage is a question that often comes up in interview-based studies around shared autonomous vehicles as it is a use case that many people have a hard time imaging in a shared vehicle. In the larger shuttle type vehicles, it seems reasonable to assume that passengers expect to be able to bring as much luggage as they would on public transport today (i.e. the passenger is able to handle the luggage him/herself without disturbing others).

However, in a service that employs microbus type vehicles, at least some passengers will expect to be able to bring far more luggage (as they would in their own car, e.g. when going to the airport or bringing home groceries). At NEVS, we investigated different concepts for separated trunk compartments assigned to different passengers of the shared vehicle but concluded, that the best and most cost-efficient solution on a service/fleet level would be to

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[20] Source: Västtrafik

let the customer book the whole vehicle if they need to transport larger items or luggage.

Child seats

One example where applying an existing technical solution becomes more complicated due to the vehicles being shared by different users simultaneously or in quick succession is the incorporation of child seats. In a privately owned passenger car, the right child seat(s) can stay in the vehicle for a long time, the time it takes to install the seat correctly is of minor importance and probably most people wouldn’t question that it is the car owners’/drivers’ responsibility that the correct child seat is installed the right way. However, in a shared AV, things are far more complicated. For trips that are booked an hour or more in advance it is possible for the AV to stop at a depot for a specific child seat to be installed, this slightly decreases fleet utilization and vehicle availability due to the extra (empty) trip, but these disadvantages are more than outweighed by the additional customers families with (smaller) kids represent. But for any spontaneous trip or immediate mobility needs the child seats would have to be in the trunk/frunk of a considerable part of the vehicle fleet and the installation of the seat would need to be very quick and easy, as to not be considered a big disadvantage compared to a privately owned car.

Another difficulty in using off-the-shelve child seats in a shared automated micro bus is the seating layout, more specifically on which seat to put the child seat. Especially for younger children, rearward facing child seats are safer than forward facing ones, so the most logical position would be the rearward facing first row of seats that many of the micro bus-type vehicles feature. Unfortunately, the isofix standard connector that is mandatory in all European passenger cars since 2014 and is therefore used by almost all child seats on the market, is designed to withstand the accelerations of a frontal crash only in the form of tensile (pulling) loads, i.e. when installed in a forward-facing passenger seat. That means to be able to install a child seat in the rearward facing front row, a completely new child seat with a new/reinforced connector optimized for compressive (pushing) forces would have to be developed, tested and approved; the cost of which would probably be high for child seat manufacturers, given the comparably small initial volumes of vehicles it can be used in.

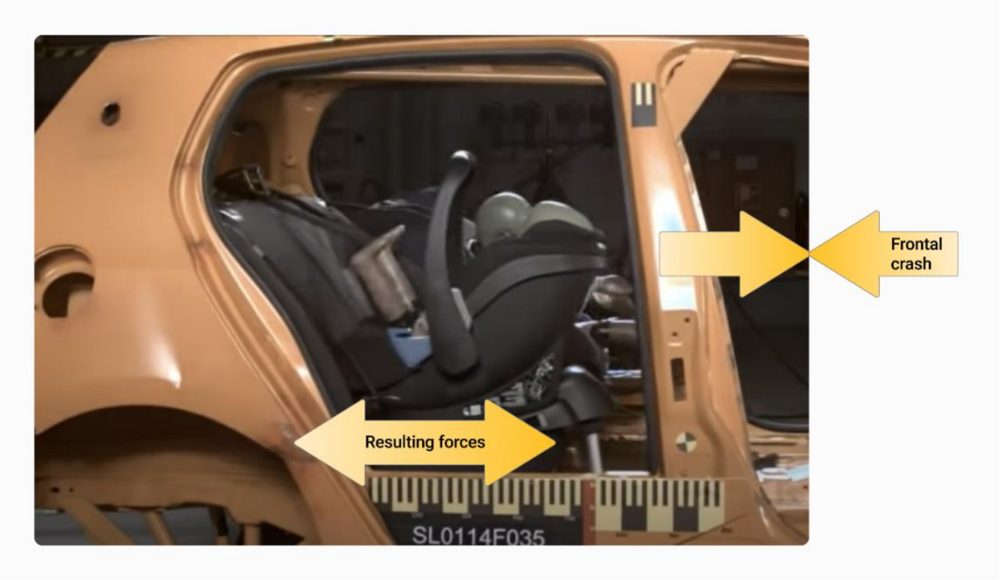

Figure 5-D: Resulting forces on the isofix-connector in a frontal crash

5.2 Vehicle software & electrical architecture

As for the challenges related to vehicle hardware described in 5.1 this chapter focuses on the unique challenges of developing the software and electrical architecture of shared automated vehicles, leaving out any more general challenges of passenger car development.

DevOps vs. traditional Waterfall

User experience and service-related software (both the “off-board” service and the on-board user interfaces) is more comparable to the development of an app or any other interactive service with constantly growing/improving functionality. For this type of software, a so-called DevOps (development & operation in parallel) methodology with fast deployments and updates and with constant interaction with the customers is a very efficient way of working.

On the other hand, software related to the driving task and other safety critical systems needs to follow a much more rigid development process as part of the “V-model” described under 5.1, more like a traditional waterfall methodology.

DevOps focuses on rapid deployment through continuous integration and delivery, fostering collaboration between development and operations teams. The emphasis on flexibility allows teams to adapt to changing requirements which is especially relevant for the completely new service and market of autonomous mobility. However, implementing DevOps in an automotive environment can require a cultural shift and handling cyber security and interfaces to safety critical systems is demanding and complex.

On the other hand, Waterfall follows a structured, sequential process with clear milestones, making it easier to plan, manage and monitor projects. Extensive documentation at each stage not only aids in maintenance and troubleshooting but is also required for the permitting process of automated vehicles. However, the waterfall methodology’s rigidity, long delivery times, limited customer involvement during development, and potential misalignment with user expectations make it unfeasible for software that is directly service and user interface related.

Ultimately, both DevOps and Waterfall methodologies have their advantages and disadvantages and since both are required for the development of automated vehicles and the complete mobility service, the difficulty lays not in choosing which to use but in combining the two methodologies, both on a technical (e.g. cybersecurity, interfaces) and organizational level.

Functions & Requirements due to new use cases

Changing the business model from the car being a consumer product to providing mobility-as-a-service with the type of user interactions described in 5.4 and 5.5 has of course huge implications for the design and user interfaces. One particularly challenging aspect from a software and electrical architecture point of view is the much higher level and frequency of changes and evolving functionality that can be expected partly due to the novelty of the service and lack of practical experience, but also due to the rapid technological development. Although the main channel through which the user interacts with the service will be a mobile app that can be updated quickly, there is also in-vehicle functionality, especially passenger comfort & entertainment related, that will have to evolve and change much quicker than in a car that is sold as a consumer product.

There are many interesting situations that might prove to be much harder to handle with no human driver present. Situations like a passenger noticing his or her forgotten bag outside the vehicle when the vehicle has already started moving, or multiple people entering the vehicle although only one has booked a seat. Situations like this will demand new solutions, that affect both software and hardware.

Drive-by-wire & AD hardware integration

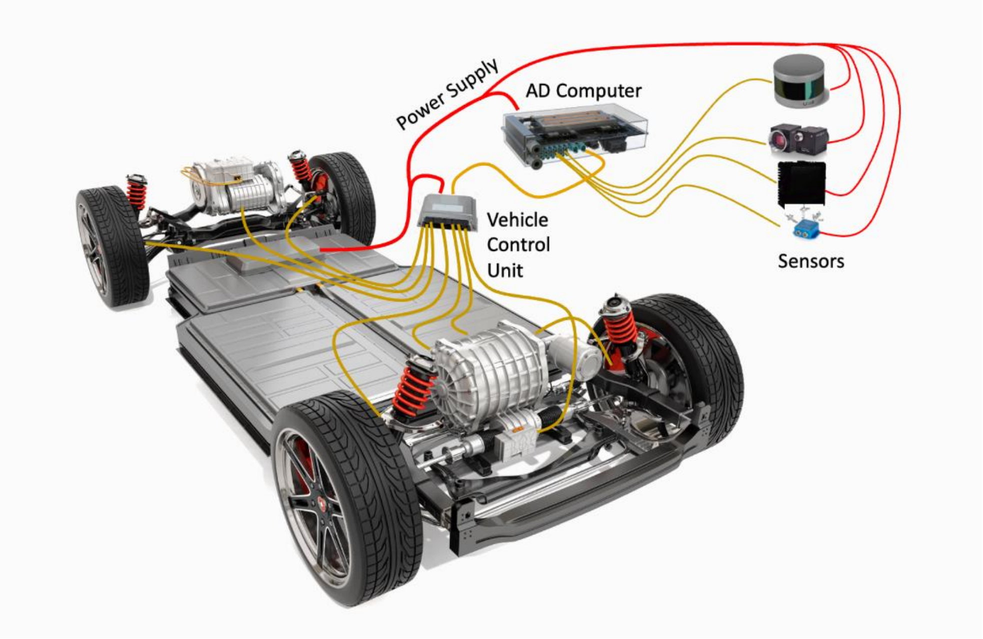

Figure 5-E: Simplified visualization of the AD-specific electric architecture of an AV. Source: Mobility as a Service AB.

The involvement of sensors and electric actuators in the driving task is by no means a new requirement. Any conventional passenger car that is available on the market today depend heavily on electronic systems for control of the vehicle's motion. For example, an electric motor assists the driver's steering and braking is controlled electronically to optimize regenerative braking in EVs. However, the driver provides the steering and braking inputs via mechanical interfaces and there's always a mechanical/hydraulic connection between the driver and the wheels that can be seen as a back-up in case the electronic systems fail.

Completely replacing the mechanical inputs from the steering wheel and brake pedals with electronically controlled actuators that receive the corresponding signals from the AD system isn't a big technical challenge in itself (and the required actuators are already built in), the difficulty lays in the redundancy that is generally required for automated systems. All logical and electronical systems have a certain risk of failure and although that risk might be comparably small, a safety critical system like steering or breaking needs to have an independent back-up to achieve the level of functional safety required for a vehicle to be permitted on public roads in Europe (the standard generally applied for functional safety in road vehicles is ISO26262). Somewhat simplified it can be said that for the back-up to be considered independent, an error that can lead to the primary system's failure must not simultaneously affect the back-up. It is not the purpose of this report (and not within the authors competence) to explain all aspects of a ISO26262 compliant drive-by-wire system, but an example that can probably illustrate the far-reaching consequences of this redundancy requirement is a failure of the vehicle’s internal power supply. Even if the battery or wiring fails, the vehicle still needs to be able to steer and brake (i.e. be “fail operational”). While in a conventional passenger car the driver can still steer and brake even without power steering and -braking support since there’s still a mechanical/hydraulic connection (i.e. the system only needs to be “fail safe”), but in a fully automated vehicle without a safety-driver this means that the primary system and its back-up also require two completely separated power supplies (e.g. a partitioned battery and two separate wiring harnesses)[21]. The same is of course true for the vehicle’s sensors: Any direction around the vehicle should be covered by at least two different types of sensors that mustn’t fail due to the same error.

Another obstacle is that (to the authors’ knowledge) currently no Tier 1 supplier has any “off-the-shelf” steer- or brake-by-wire system ready for serial production. The authors believe that this is mainly due to the still comparably small market of Level 4 AVs compared to the market volume of conventional passenger cars (where the added value of a “true” drive-by-wire system is much smaller).

5.3 AD software

Developing AD software poses a myriad of challenges at the intersection of artificial intelligence, robotics, and automotive engineering and it is not the purpose of this chapter to describe all these challenges in detail, but rather give a general overview and basic understanding especially for non-experts.

Non-deterministic behavior of neural networks

As mentioned in 4.2, AD software usually consists of different mixes of deterministic rule based and non-deterministic neural network / machine learning approaches (but all AD systems involve neural networks to some extend).

Rule-based programming is predictable/deterministic, i.e. through analyzing the code it can be determined why the system reacted as it did to a certain input or how it will behave in the future under defined boundary conditions. However, it is not possible to design a decision-making algorithm for AVs that is purely based on manually programmed rules as the number of possible situations and scenarios that the vehicle can encounter and that would need to be encoded is technically infinite. The machine learning approach provides that flexibility, but using the results of machine learning at the core of the decision-making process has two major downsides: Firstly, it makes it very difficult to determine why the system behaved the way it did in a certain situation, and in case of an accident, it is this non-deterministic behavior that leads to very difficult legal and moral implications. Secondly, if there’s specific traffic rules that human drivers usually don’t abide by, the system’s reliance on human driving training data as its main input can lead to an AV violating traffic rules.

A good example of this problem is the case of a driverless cruise vehicle running over and dragging a pedestrian in San Francisco in October 2023[22]. In the seconds before the accident, a pedestrian was j-walking through the vehicle’s lane at the far end of the crossing.

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[21] Tesla claims that the Cybertruck has a fully redundant steer-by-wire system without mechanical back-up which would make it (to the authors’ best knowledge) the first serial production vehicle to fulfill this requirement. The authors couldn’t confirm if the system is ISO 26262 compliant.

[22] For a detailed analysis of the accident, please refer to Koopman (2024), “Anatomy of a Robotaxi Crash: Lessons from the Cruise Pedestrian Mishap” [2402.06046] Anatomy of a Robotaxi Crash: Lessons from the Cruise Pedestrian Dragging Mishap (arxiv.org)

Because the AD system anticipated from the pedestrian's trajectory and based on its training data, that the pedestrian would have left the lane by the time the vehicle had traversed the crossing, the vehicle started moving into the crossing when the traffic lights turned green. While this is consistent with how most people usually drive, it violates a Californian traffic rule that states, "The driver of a vehicle approaching a pedestrian within any marked or unmarked crosswalk shall exercise all due care and shall reduce the speed of the vehicle". This is a good illustration of why machine learning based systems still need to be combined with rule-based systems as it can be anticipated that the general public will expect AVs to follow traffic rules much closer than what is generally expected from a human driver.

Data management

A couple of years ago, one could read everywhere that "data is the new gold". But at least in the context of AD you could argue that, since there's far too much data, most of it is of little value and even the good parts need a lot of analyzing and refinement to become valuable, data is more like the dirt one needs to dig through when looking for gold than gold itself. From the authors' experience from developing business plans and working with investors there's a widespread belief that selling data should represent a huge additional source of income for AD companies, but until proven otherwise, we see it mostly as a huge challenge that increases cost not profits.

Fully automated vehicles generate vast amounts of data from various sensors such as cameras, lidar, radar, and other sources. Combining data from different sensors, known as sensor fusion, is essential for creating a comprehensive and accurate perception of the vehicle's surroundings. Integrating and synchronizing this high-volume stream of data from diverse sensors is a challenging task and requires sophisticated hardware and algorithms. To fulfill the real-time requirements of the AD system's decision-making process and reduce the already huge data streams to and from the cloud, as much data as possible is processed "on the edge" (on board the vehicle). However, managing computations on resource-constrained edge devices also poses technical challenges.

But even the data stored "off-board" comes with multiple challenges. Storing and analyzing historical data is essential for improving autonomous systems over time. Managing vast datasets for long-term storage, retrieval, and analysis while privacy compliance and cybersecurity add additional layers of complexity is already challenging and will only become harder with a broader roll-out of AD vehicles.

Edge cases & "extreme" weather conditions

Handling extreme edge cases that none of the other vehicles of the AD company's fleet has ever encountered before remains of course an obvious challenge (i.e. the so-called "long tail", if there's many such scenarios, some also refer to this as the "heavy tail"). However, the authors believe that this challenge will become much less relevant as soon as it is proven beyond any reasonable doubt and generally accepted that AVs are safer by a considerable margin than human drivers (which WAYMO claims they already can, at least for non-fatal crashes[23]).

Currently, the much larger challenge seems to be bad weather conditions. Although no AD company has (to the authors' knowledge) explicitly stated weather conditions their AD

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[23] Kusano, Scanlon, Chen (2023), *Comparison of Waymo Rider-Only Crash Data to Human Benchmarks at 7.1 million Miles*

system cannot handle, it seems obvious from the places where most test fleets are deployed and from the limitations to when the services are operational, that heavy rain and snowfall are outside of most AVs so called operational design domain (“ODD”). And although there’s also limits to the weather conditions in which humans can drive, it still remains to be proven that AVs can reach at least the same level as an average human driver when it comes to heavy rain or snow. There is some evidence that this can be achieved, e.g. the authors have seen videos of Mobileye’s vehicle navigating extremely difficult weather conditions in Grorudalen, Oslo and Sensible 4’s vehicles operating in heavy snow fall but haven’t experienced it themselves yet.

5.4 System-of-systems complexity

Establishing a fully functional service entails a complicated set up of different systems from different actors, all of which must cooperate seamlessly as a cohesive unit. Building a "system of systems" (SoS) involves the integration of multiple independent systems into a larger framework to achieve specific objectives. Beyond the vehicle itself and the integration with the AD-system, a significant array of systems exists external to the vehicle. While many of these systems are established and reliable, they have not yet been integrated and tested as part of an integrated system of systems. Please refer to chapter 4.3 for an overview of the different systems clustered into A. Customer interfaces (front-end), B. Mobility platform (back-end) encompassing service orchestration, vehicle management, on-site fleet operations, user Management, as well as C. Vehicle and City interfaces.

The specific tasks that the complete system-of-systems needs to accomplish can be described in the form of use cases/user scenarios. The figure below shows an example of a very basic and simplified user scenario:

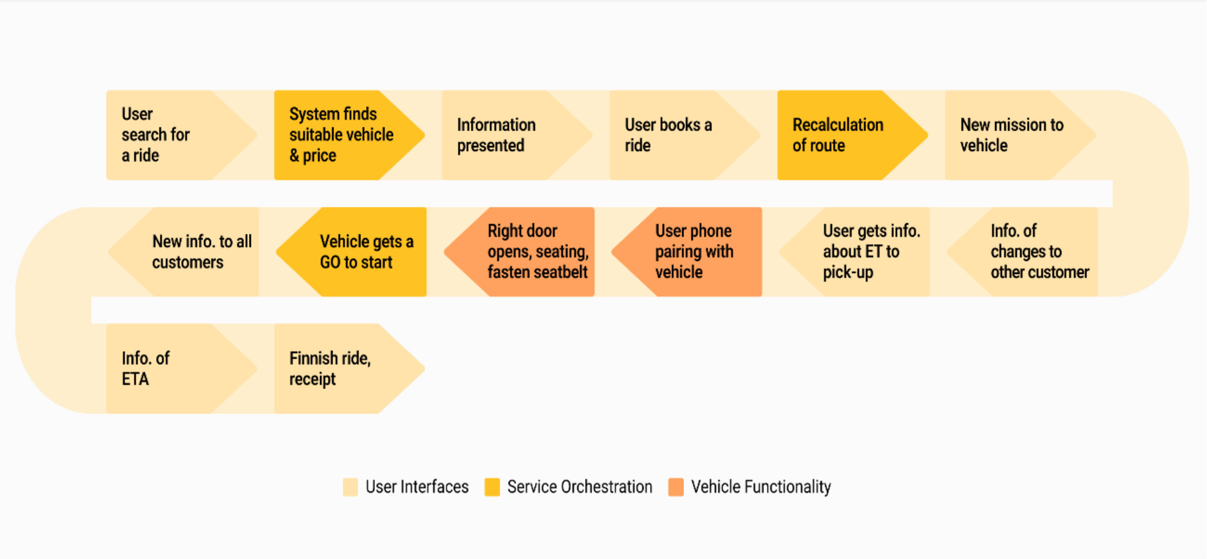

Figure 5-F: Simplified user scenario and the complexity of system of systems. Source: Mobility as a Service AB

This example of a simplified user scenario involves multiple sub-systems. Both front-end applications like mobile app, external or internal vehicle screens, and back-end functionality such as route optimization, finding the right price, payment, identification. Furthermore, it involves safety critical in-vehicle systems, including the AD-system. This process should be executed in (near) real-time with dependencies on external systems. Adding hundreds of user scenarios including edge cases there are plenty of things that can go wrong both when developing and integrating the systems and over time when sub-systems and APIs are updated.

There are several general challenges and problems associated with design, development, and operation. Addressing these challenges requires a holistic approach to system engineering, involving robust architecture, effective communication, and continuous supervision and management throughout the lifecycle of the overall service and its subsystems. Some examples of challenges:

Interoperability: Ensuring seamless communication and interaction between different systems with diverse architectures, technologies, and standards is a common challenge. Achieving interoperability is crucial for the effective functioning of the SoS.

Complexity: As the number of subsystems increases, the overall complexity of the system also rises exponentially. Managing this complexity poses challenges in terms of design, maintenance, and understanding the overall system behavior.

Coordination and Control: Coordinating the activities and operations of individual subsystems to achieve the overall objectives of the SoS can be complex. Defining control mechanisms and managing dependencies is critical.

Security: Integrating multiple systems increases the potential attack surface, making (cyber) security a significant concern. Establishing robust security measures to protect against cyber threats and unauthorized access is crucial.

Data Management: Managing data across multiple subsystems with different data formats and structures can be complex. Ensuring data consistency, integrity, and availability is a challenge in a complex SoS.

Lifecycle Management: Coordinating the lifecycle activities of individual subsystems, including development, testing, deployment, and maintenance, is crucial for the overall functionality of the SoS.

5.5 Service & user interaction (UI/UX, HMI)

Examining the customer journey and the various touchpoints where the user interacts with the service unveils numerous challenges and trade-offs that require careful consideration. By trade-offs, the authors refer to the fact that neither the service, nor a specific vehicle can fulfill all use cases and customer needs in the optimal way for everyone. Therefore, it is crucial to understand, how important a certain function or property is for how many users but also how much of one function or property can be sacrificed to improve another function or property.

There is an important distinction to be made between the service, which may include several types of vehicles, and the specific vehicle that has its physical limitations (for a more detailed discussion of the trade-offs directly related to vehicle hardware, please refer to chapter 5.1). In practical terms, this implies that for a service aiming to cater to a broad audience, different vehicles can be tailored to specific needs—whether standard or purpose-built, manually operated or autonomous—for varying user requirements. For instance, a fleet can include vehicles designed for wheelchair passengers, rides tailored for those with severe allergies, exclusive services for women, family-friendly rides with vehicles pre-equipped with child seats, or rides accommodating passengers with lots of luggage. Having a larger and more flexible fleet allows for pragmatic and optimized solutions to a wider array of use cases.

Once the overall use cases and the target audience(s) for the service are established, a deeper exploration of the customer journey is necessary. Understanding the desired experience and anticipating potential pain points enables the definition of the most effective solutions through the various identified touchpoints. A comprehensive service design requires a holistic approach, ensuring that the service aligns with user needs and expectations at every step of their journey.

The NEVS protype vehicle (Sango RC1) was developed with the ambition to solve several use cases and attract different customer groups with an interior design balancing privacy and social space. Also, in the service design we identified pain points and had solutions for many of the challenges. Those are of course specific to the planned service concept and vehicle size, but the underlying logic could certainly work as an inspiration for other vehicle developments.

PRIVACY MODE

Privacy walls divide the vehicle in 4 comfortable private lounges

SOCIAL MODE

The middle row is automatically pushed back to create an extra comfortable lounge

FAMILY MODE

6 people sitting comfortably in three rows, especially suitable for families

Figure 5-G: Sango flexible interior design accommodating different use cases. Source: NEVS

Privacy vs. everything else (space, flexibility, view/motion sickness, social interaction, etc.)

A significant advantage often associated with owning a personal vehicle is privacy. In your own car, you enjoy a dedicated space where you can crank up the volume on your favorite music, talk on the phone without restrictions, and avoid the need to share space with other passengers. The challenge lies in replicating this sense of personal space and privacy in shared mobility solutions without compromising on other valuable benefits. How can a comparable feeling of individuality be achieved in a shared ride without sacrificing the numerous advantages of shared transportation?

Potential solutions:
Hardware: Different seat layouts for different use cases; designing seats with curved headrests and privacy walls between customers; individual screens at each seat; one door per seat that can open individually

Software: Individual communication along the customer journey; individual passenger identification; optimized planning for seating and stops so passengers entering or leaving the vehicle don’t disturb anyone else

Service design: Offer both shared ride and individual ride/own vehicle; specific rides for different categories (e.g. “women-only” or “children free” rides).

Interaction with no human present

In a normal taxi today, the passenger communicates a lot with the driver without even thinking about it. Possible interactions include aspects such as the driver confirming that the passenger is entering the correct taxi, guiding them to the appropriate door for entry, assisting with luggage, verifying the destination, ensuring the proper use of seat belts, and installing child seats when required. Throughout the journey, the driver remains responsive, answering potential questions, and accommodating changes to the drop-off location. Upon reaching the destination, communication extends to ensuring the safety of opening the door and verifying that the passenger has collected all their belongings. In unexpected or emergency situations, the lack of a physical driver in the vehicle can become especially noticeable, just imagine your kid still being outside and the door is closing –shouting at the driver to stop would be much more intuitive than clicking through an app to find the right command.

Potential solutions
Hardware: Individual screens with updated information and as a communication channel; physical buttons for emergency stop; cameras to detect and support safe egress

Software: smart signals (e.g. chimes/signs/voice) to support with ingress/egress, remind of seat belts, other safety related issues and not to forget personal belongings; continuous information in screen and app on estimated time of arrival, etc.

Security – feeling safe

Feeling safe, especially for women, when no one else is around and you are not protected by the crowd is a potential problem in a shared mobility service (with or without a driver). This is of course related to the question of privacy mentioned above, but with a much higher importance and immediacy. It also relates to the whole customer journey, when often not the ride itself, but the pickup and drop-off are the crucial moments both for actual and perceived security.

Potential solutions
Hardware: Identification of both the one who books the ride and the one entering the vehicle; in-cabin camera surveillance, “privacy walls” separating passenger seats,

Software: Instant communication with traffic control; silent alarm through app and in vehicle screen

Service design: Female rides only; adjusted pricing during evening hours, identification of all passengers (people generally behave better if they are aware that the service provider can identify them); offering safe stops (good lightning, crowded with people, etc.)

Design for heavy usage

Traditionally, cars have been designed to be sold to private customers, where “soft” properties like look and feel are often more important than purely practical aspects like rigidity and reliability and it can be expected that customers take better care of his/her own car than of a shared vehicle. When designing service vehicles or public transport vehicles it is more important to design for low wear and tear as well as good cleanability. But in this case, when providing a service that competes with the private car, both practical and “soft” aspects need to be balanced.

Potential solutions
Hardware: Balance how private cars vs. busses and trains look. Make it possible to change parts and refurbish the interior after a certain period of usage, camera, and communication channels for surveillance.

Software: reminding of rules, inform about surveillance

Service design: Point system for clean vehicles, reporting tool for bad cleaning.

MOIA has in their service in Hamburg about 500 custom-built minivans which the authors think are a good example of an interior design that combines easiness to clean with a feeling of exclusivity.

Figure 5-H: MOIA and VW vehicle – interior design. Source: MOIA

5.6 Permit & homologation

Most challenges around permitting and homologation of AVs originate from the fact that many rules and regulations for road traffic and vehicle safety where written or are based on conventions from a time when AVs were not yet envisioned, namely the Vienna convention from 1968 and regional as well as national amendments and interpretations thereof[24].

While improvements and adaptions are being made and have already been made at the top level (e.g. in 2021 an amendment to the Vienna and Geneva conventions was made to generally allow for a digital driver instead of a human) a lot of limitations remain in more specific rules where the connection to a human driver is more indirect. One of the fundamental purposes of the European type approval process is that a vehicle that is approved in one country, automatically gets approval for all other European countries, which, in the context of AD, is a logic that fits Level 5 autonomy but isn’t especially helpful when Level 4 is the focus.

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[24] Jenny Lundahl: *Automated driving – Overview of current and upcoming regulations, ver. 0.5* (2023)

Different regulations are written for different levels of automation

A lot of misunderstandings and inefficiencies in the discussions around legal requirements for autonomous vehicles stem from the fact that different stakeholders seem to focus on different levels of automation. E.g. the latest regulatory activity in Sweden, “Promemoria Automatiserad körning” puts its main focus on firstly, regulating which areas already type approved fully automated vehicles are allowed to drive in and secondly, that the person that activated the AD system remains responsible for the AD system’s behavior. In the authors’ opinion, the first focus seems to assume Level 5 automation (for which there’s no urgency) while the second focus is clearly a Level 3 regulation that is difficult to apply to fully automated vehicles. And while the question of Level 3, 4 or 5[25] automation might be a rather general example, there are more specific cases that can describe the difficulties of applying conventional passenger car regulations to fully or highly automated vehicles.

Rearward facing front row seats: Not illegal, but not fully legal either

A good example of how existing regulations become problematic for AVs in ways that were clearly not intended when the regulation was written is the integration of (first row) rearward facing seats that many of the AD Micro bus type vehicle concepts feature (as illustrated in Figure 4-D: Seating layouts featuring rearward facing front row seats in Zeekr M-Vision (left), Zoox (middle), and Cruise Origin (right). A seating layout with two rows of seats facing each other is a good way of making use of the new technology as it leads to a vehicle with great interior roominess that doesn’t take up much (road) space and there’s no (European) legislation that specifically forbids it. However, there’s a chain of interdependent regulations that stand in the way of a vehicle with this seating layout being type-approved in Europe. As long as there’s no separate AD vehicle type classification, vehicles like e.g. the Cruise Origin or the Zoox vehicle would almost certainly be classified as M1 vehicles (vehicles for the transportation of passengers with not more than 8 passenger seats).

One of the many legal requirements an M1 vehicle needs to fulfill is a physical crash test with test dummies that demonstrates the crash safety of the vehicle for the front row passengers (as those seats are the ones most commonly used). Although a rearward facing seat is generally considered to be safer in a frontal crash, there’s no certified way available today to prove this because there are no certified crash test dummies available that measure the accelerations and forces in a rearward direction. So, in summary, although rearward facing seats are most probably safer than forward facing ones, the lack of certified crash test dummies for this type of test makes it impossible to prove this seating arrangement’s sufficient safety which is a legal requirement of the type-approval process. Furthermore, it’s important to note that there’s no such requirement for the rear seats (presumably since those seats are much more seldomly occupied), which means that a rearward facing seat is perfectly legal in the second or third row of seats and there are plenty of M1 passenger cars with rearward facing seats in the back rows that have been type approved (mainly minibuses or larger vans), so an AD micro bus with rearward facing seats would be equally safe as already type approved passenger cars but since AVs need to comply with rules that were written for a different kind of vehicle this is currently not compliant with legal regulations.

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[25] For a detailed description of the different SAE levels of driving automation, please refer to SAE Levels of Driving Automation™ Refined for Clarity and International Audience

Distribution of responsibility between AV provider and authorities

Probably most people would agree that it makes perfect sense that it is the AD company's and OEM's responsibility to prove, that AD system and vehicle can handle a defined set of weather-, traffic-, or other boundary conditions at an acceptable level of safety. The bigger challenge for AD companies and OEMs lays however in the fact that the way the permitting process in Europe works today, it is, to a large extend, also their responsibility to determine what that set of possible conditions for a given area should be, how safe that "acceptable level of safety" is and in some cases even how to prove it.

It can be seen as emblematic for the challenge described above that the term "operational design domain" ("ODD") is today used by many to describe the scenarios and conditions that the AD system is capable of operating in (i.e. a property/capability of the vehicle), while others use the term ODD to describe the scenarios and conditions that are present or can occur in a specific area (i.e. a property of the road or area). In the author's opinion, the term ODD should be used to describe the capability of the AD system and vehicle while "Target Operational Domain" or "TOD" (as described in ISO/AWI 34503[26]) should be used to describe the scenarios and boundary conditions that can potentially occur on a specific road or in an area. Defining the terminology like that helps to avoid misunderstandings and raises awareness for the fact that what the AV is actually capable of and what it needs to be capable of to operate safely in a certain area are separate questions that should be addressed independently.

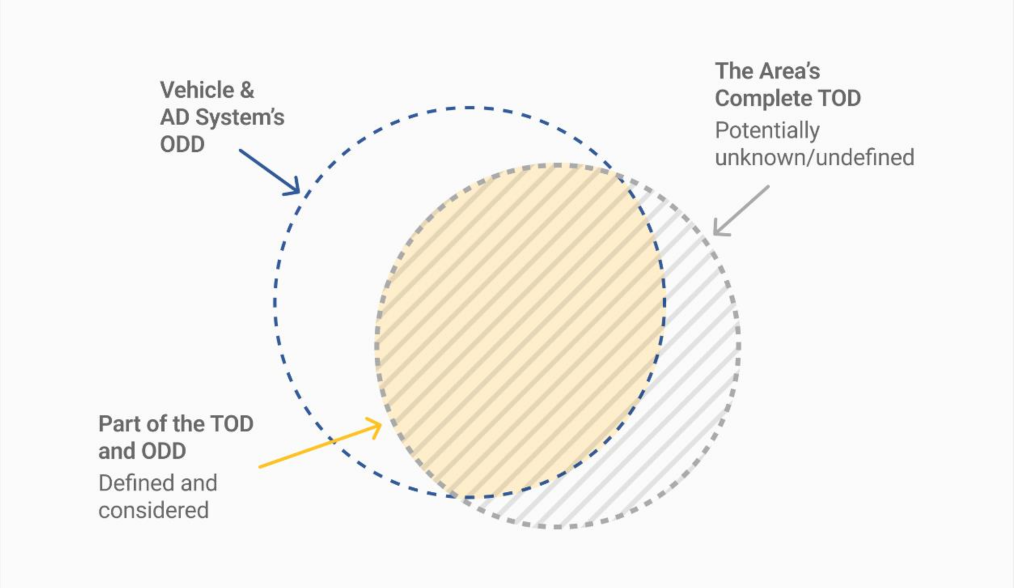

Figure 5-I A mismatch between the AV's ODD and the target area's TOD can lead to uncertainty in the permitting process and operational risks. Source: Mobility as a Service AB.

Potential solutions

Although it might seem hard: A clear specification/guideline of how safe is safe enough will be required at some point and the authors believe that it shouldn't be every AV manufacturer's individual responsibility to provide this specification or guideline.

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[26] ISO/AWI 34503 – Road vehicles – Taxonomy for Operational Design Domain for Automated Driving Systems - ASAM

Interestingly, EU Regulation 2022/1426 states that “*the manufacturer shall define the acceptance criteria*” but proposes then in a related footnote that “*for instance based on current accident data on buses, coaches, trucks and cars in the EU, an indicative aggregated acceptance criteria of 10-7 fatalities per hour of operation could be considered for market introduction of ADSs for comparable transport services and situations.”* So, one could argue that, although the regulation asks the manufacturer to propose an acceptable safety level, it also indicates what the EU Commission would consider to be safe enough. While this is a good step forward, solely focusing on the number of fatal accidents per hour of operation would overlook non-fatal accidents or a possible risk transfer towards a specific group despite overall risk reduction.

A first step towards a more pro-active role in safety assessment and requirement setting could be to work with multiple AV manufacturers towards an independent assessment of a TOD (by the road authority itself or delegated to an independent third party) for an area of intended AV operation, providing the AV manufacturers with a clear specification of which scenarios and conditions they need to prove their system’s capability for.

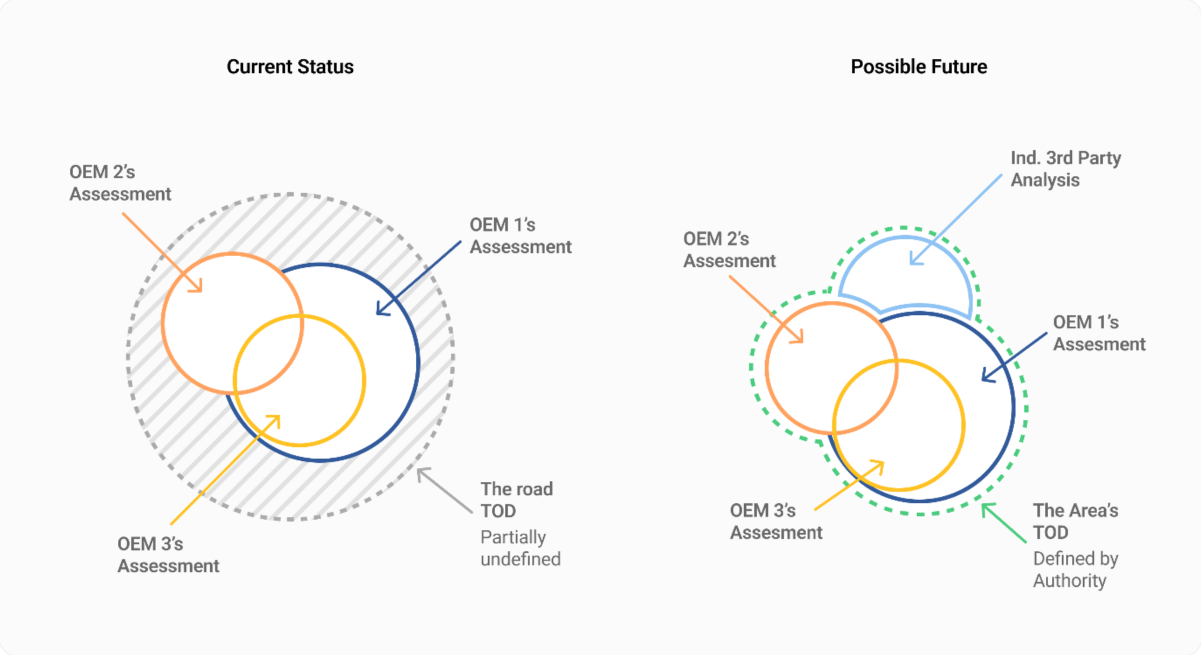

Figure 5-J: Achieving an OEM independent definition of an areas TOD by combining multiple OEMs' assessments with an independent 3rd party's analysis. Source: AstaZero

However, it also needs to be mentioned that while it’s true that this somewhat uneven distribution of responsibility is a challenge, one needs to be aware that this challenge is sometimes exaggerated and in many cases where AD companies or vehicle manufacturers blame the difficult permitting process for the slow roll-out, the actual origin might lay in the fact that AD company and vehicle manufacturer can’t agree on their internal distribution of responsibility. That means their inability to receive a permit is merely where this internal conflict becomes visible.

A legal person as ultimately liable/responsible

A big legal concern of legislative authorities in Sweden and other European countries seems to be the requirement, that in case of an accident in which someone gets injured or killed, there always needs to be an individual to be ultimately responsible/liable. However, the UK

Automated vehicle bill announced in November 2023[27] makes the AD company, rather than individuals, responsible for a vehicle when it is self-driving (i.e. this could be seen as a kind of "driver's license" for a legal entity). Furthermore, one should not forget that even in conventional passenger cars today, a lot of systems are controlled by software (including non-deterministic machine learning sub-systems like e.g. the object detection of an advanced driver assistance system, ADAS) where it might ultimately not be possible to determine a responsible individual in case of a malfunction. So, if the goal was to prevent this kind of scenario from happening, it might already be too late.

Differences between Europe and the US

The grave implications that functional safety requirements have on the complete AV's electrical architecture described in 5.2 are (indirectly) among the main drivers for their slower roll-out in Europe. While the European type approval logic requires the OEM to prove the fulfillment of the functional safety requirements described in 5.2 before allowing operation without a safety-driver, the US permit is based on self-certification logic. Thus, it is possible for an AD company to get a state permit to operate fleets of retrofitted passenger cars on public roads with neither a safety driver nor a redundant drive-by-wire system as long as their internal safety process deems that solution to be safe, while the same technical solution would not be permitted in Europe.

5.7 Effect analysis

It's generally agreed that the entire transport/mobility system and society would be affected by a large-scale introduction of autonomous vehicles. However, the details of how and to which extent society as a whole and the individual's life would be affected are complex with many unanswered questions and different perspectives to consider. A possible way to approach this complexity could be to ask the following questions:

1. Will the customer embrace the service and to what extent will they use them?
2. Can we (including all stakeholders) provide that service in an economically viable way?
3. By how much will the number of rolling and parked cars be reduced with an introduction of these kind of services in different application areas?
4. Depending on the answers on the above question, what effect will that have on the mobility system and society as a whole and what is the societal value of this effect?

A lot of studies have been done that have simulated the demand, supply and effects on the overall traffic situation of a city, e.g. Lisbon, Helsinki, Oslo and Gothenburg[28]. Also, interview-based surveys have been conducted, asking citizens and potential customers if they would change their travel behavior if on-demand services were available. In smaller communities where there are existing DRT services, some evidence of the effects related to traffic situation, accessibility, etc. can be retrieved. These studies and projects create

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[27] Automated Vehicles Bill [HL] 2023-24 - House of Commons Library (parliament.uk)

[28] Refers to a study that aims to investigate the potential effects shared mobility can have on future transportation, that include the mentioned studies: Simulating the Impact of Shared Mobility on Demand: a Study of Future Transportation Systems in Gothenburg, Sweden | International Journal of Intelligent Transportation Systems Research (springer.com)

important inputs to the discussion but are somewhat limited in answering the overall question. Some reasons why this is so difficult:

- It is extremely hard for people to imagine how they would use a service that they only have a theoretical conception of. When the authors were involved in user tests with prototype and mock-up vehicles at NEVS, many users gave different answers after a testride than they had given earlier in purely theoretical surveys. Being able to touch and enter the vehicle and experience the service in a somewhat realistic setting made it much easier for users to imagine the service being a real life alternative. But even “behind the fence”-testing in a rolling prototype is still a long way from using the service in one’s everyday life, so it can be expected that there’s still a lot of room for improvement when it comes to realistic user feedback.

- The direct costs per driven km like depreciation and maintenance of the vehicle, AD system cost, and cost of technical support and operation can be calculated quite accurately. But it’s much harder to calculate the amount of km the vehicles need to drive to achieve a certain number of passenger km, since many parameters that are of great importance for the overall cost like average trip distance, occupancy, empty milage, required number of vehicles for a defined service level and many more are very dependent on the details of the actual implementation of the service. There is some experience and data that can be derived from somewhat compareable existing services, but for a large-scale roll-out, making realistic predictions for the parameters described above requires quite detailed simulation models of the overall service.

- Many of the simulation models that are still used for traffic planning today were originally developed for traffic planning based on existing modes of transportation and at times when much less public data was available, and computers had a lot less computational power than today. Thus, these legacy simulation tools are generally not well suited for modelling new modes of transportation with the level of detail that’s required to make realistic predictions. A specific limitation of many simulation tools is that they model mobility demand and resulting traffic as a flow and not as individual travelers and vehicles. These flow-based simulations work somewhat accurately as long as a neglectable share of journeys are made in shared AVs, but results become less applicable quickly in scenarios where shared AVs reach significant market shares. There are agent-based tools available today that would be capable of more detailed simulations at a traveler and vehicle level, but many planners stick to their legacy tools that they’ve invested a lot of time and money in optimizing.

- The actual value of fewer vehicles and increased sustainability on a societal level is hard to quantify. In General, more attractive cities are beneficial for business and commerce, lower stress levels and better air quality reduce healthcare costs, increased accessibility improves fairness, and freed-up space decreases infrastructure expenses. However, although all these benefits are certainly tangible it is difficult to put a number on the collective value of these factors to society.

Related to the point above – today’s mobility system revolves around private cars. However, there have been plenty of initiatives that aim to increase the burdens associated with owning and driving a private car, particularly in urban areas. Concurrently, there is a notable subsidization of public transport, averaging 50% in Sweden, alongside a concerted effort to promote cycling and walking. We can foresee the persistence of such trends, prompting a return to the initial consideration – what will the perceived "value" of owning a personal car in the future be in comparison to travelling with on-demand shared autonomous vehicles. It is safe to say that more shared mobility is good for society, but we currently lack many of the tools required to quantify the positive effects well enough given the magnitude of the expected change.

5.8 Business model & Business case

The definition of a business model is how a company creates, delivers, and captures value. So, at a general level it is fairly simple – the demand for mobility is there, and companies in the mobility ecosystem capture that value by delivering mobility as a service, when people need it. And the ability to eliminate the cost of the driver while at the same time scaling the service and increasing efficiency will make the service commercially viable. That's the theoretical model.

However, the business model and the business case have some built in complexities and paradoxes:

Challenge 1 – no market, no vehicle or no vehicles, no market

OEMs usually build their business case on large volumes that are sold on a global market. With advanced and validated models for expected demand, they predict sales and resulting revenues. But in the case of purpose-built AVs, that's a lot more complicated – will the market be driven by service providers for robotaxi services like the first deployments in the US, or will it evolve as a part of public transport, like many experts think will be the case in Europe. And if the public sector is the main customer of vehicles, that entails additional questions like what type of vehicles in which volumes can be expected, and will it still be allowed to offer private robotaxi services that compete with public shared mobility or will those services be banned? So, it is very hard to build a solid business case, especially for an OEM depending on long term plannability and large production volumes.
On the other hand, fleet customers and mobility service providers have a hard time building up a market and quantifying a future demand for vehicles if there are no such vehicles currently available that could be tested and experienced by the general public in the context of a fully operational mobility service. This situation is further aggravated by the fact, that the public procurement process via public tenders is generally not well-suited to procure large volumes of a vehicle that doesn't exist yet.

So, the market is in a "catch 22" – situation. Public and private fleet customers can't commit to large future volumes, which prevents OEMs and their suppliers from investing in the serial production equipment and designs that would be required to drive down the cost per vehicle to the levels required for the large-scale roll-out that would lead to fleet customers being able to commit to large future volumes.

Challenge 2 – difficulty in predicting customer behavior

It is common knowledge that owning or leasing a car is inefficient and expensive when considering all costs and the fact that the car is parked on average 97% of the time. However, there is still evidently a market, and customers are willing to pay for the flexibility, convenience, and (sometimes) status that the car provides, and there is scientific evidence that customers underestimate the actual cost of owning a car[29]. There's plenty of other examples where people spend surprisingly much money for things they use quite seldomly, lika a boat, a summer house, or power tools that are used only every fourth year – at a first (purely economic) glance owning these things makes not much sense. With autonomy, where one doesn't even need to drive themselves, it becomes even more apparent that the the car can be shared among users to use resources and money more efficiently, but the question is whether customers value this to a large enough extent. Many experts and simulation studies predict that the demand for this kind of mobility service will be high when prices per journey will drop, but there's of course no hard "proof" and one can never be completely certain. This is a challenge of the overall business model, that customer may not behave as we thought they would, which makes real demand hard to predict.

Challenge 3 – peak demand defines required number of vehicles

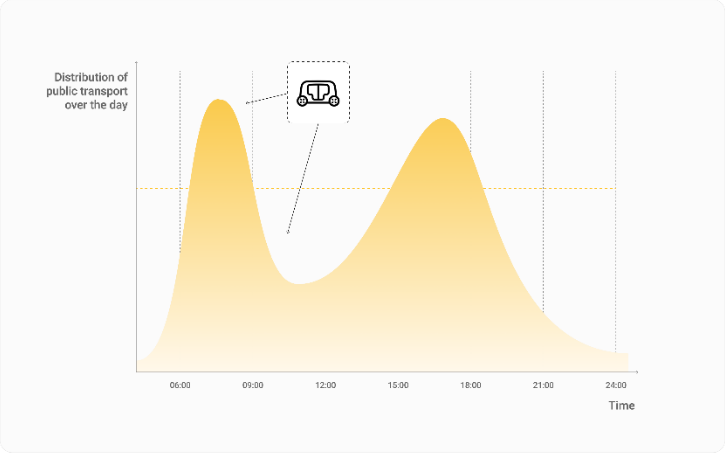

Figure 5-K. Public transport during a weekday. Source: Mobility as a Service Ab.

The second challenge is that to capture the value the service needs to be relatively attractive and for that, vehicle availability needs to be always good enough. Because if a customer experiences a delayed pick-up in a time critical situation, he or she might try again another time, but the service provider will probably not get a third chance. This is a common challenge in mobility services including public transport. In areas with few people, there may not be sufficient availability, and without sufficient availability, the service does not become attractive enough. Including in this challenge is the peak-time problem, i.e. the fact that the supply is dimensioned by the travel demand during peak times which leads to low utilization during off-peak hours. This challenge is already there today, although for line based public transport, removing the driver will ease the burden somewhat due to both reduced cost and not having to consider labor regulations for drivers.

Challenge 4 – distribution of revenues along the value chain

Above, the business model is described on an eco-system level. But for companies within that eco-system the eco-system level is of minor importance. Each company has it´s part depending on what role it takes along the value chain and what value it is trying to capture. So, looking into the different actors' challenges:

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[29] Andor, Gerster (2020): *Running a car costs much more than people think — stalling the uptake of green travel*

OEMs: Today, OEMs make money by producing and selling as large volumes of vehicles as possible on a global market. So, one could argue the goal is to provide as many cars as possible to serve a given mobility need, to some extent taking advantage of the gap between the actual and perceived cost for owning a car that was described above. The business model when offering mobility as a service with autonomous vehicles is to provide the same amount of mobility to the same number of customers with as few vehicles as possible. The challenge for OEMs becomes to produce fewer vehicles in an efficient way and find price models where they can capture the lifetime value of vehicle as a service. As can be seen in the image below, operational costs take an increasing part of the overall cost of providing the service when the cost per vehicle drops due to increasing production volumes:

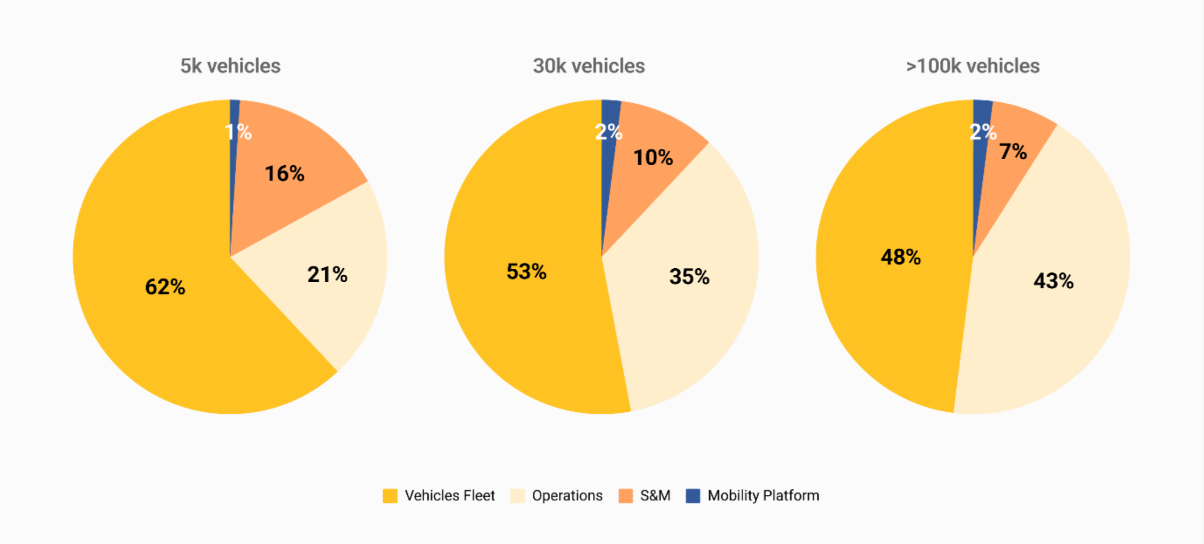

Figure 5-L Cost of the overall service. Calculated based on NEVS business case. Source: NEVS

ADS: The business model of most AD (software) companies relies on the premise that what is developed can be offered at scale on a global market. However, it is extremely costly to stay at the forefront of development, and what was cutting edge yesterday can become a commodity today. The challenge for AD companies is to achieve profitable growth in a limited market while safeguarding unique system properties.

Service providers: PTA (Västtrafik, Ruter), PTO and private ride hailing companies (Waymo, Uber, MOIA) might end up to be at the top of the value chain but they will face different questions.

Public Transport has to provide everyone with the same service, at the same price. So, it might be hard to capture the full value and fully utilize any individual customers' willingness to pay completely. Furthermore, procuring a service including a fleet of vehicles and operations contracts via long-term public tenders can be risky since demand is hard to predict. In what way future tenders will be organized and how PTAs can balance risk will be crucial questions.

Private service providers have today a somewhat unclear market position and addressable market. Will they be allowed to offer this kind of services, and will they compete or collaborate with public transport? In the US this is not much of a question today, which gives companies like Uber or Waymo a great potential in the taxi/ride hailing segment, competing with human driven taxis, but with a 50% lower operational cost. In large parts of Europe this will probably not be an option, looking at how e.g. the e-scooters market has been regulated after an initial phase of light or no regulation. Although there are some general trends, the exact shape of the future market for shared autonomous mobility can still be considered too uncertain for a private company to invest large amounts.

Operators: Public transport operations or taxi operations are stable but low margin businesses today, mainly consisting of handling staff and maintaining vehicles. The main way a transport operator can differentiate itself from competitors is to be better at long term and daily planning of vehicles and staff. The overall market volume for operators is likely to shrink if drivers disappear from the vehicles and planning and orchestration is mainly done by AI-based systems. This might not be an immediate problem for operators, but something to consider.

5.9 Vehicle Production at (the right) Scale

it may be surprisingly easy to design a competitive electrical vehicle with the help from experienced automotive engineering consultancy firms, but as many startups and other newly established EV manufacturers have learned the hard way, it is surprisingly difficult to industrialize the products and compete with existing OEMs in what has been their core business for a long time: Serial production. The whole automotive industry in general and OEMs in particular have optimized and perfected production- and sourcing processes for a very long time and achieved incredible levels of quality, reliability and most importantly: cost efficiency. But these levels can only be achieved through high levels of automation and huge (upfront) investments in specialized tooling.

One of the questions the authors have been asked the most over the years by investors and potential fleet customers is “how much will one of those vehicles cost?”. In most cases the intuitive expectation of the person asking the question is based on the cost of a “comparable” passenger car or minibus plus maybe a premium of 10-50% for sensors and other specialized equipment.

Although the expectation is correct in that way that sensors, a more complicated electrical architecture and larger doors are driving cost upwards, it misses the much larger influence the production volume has on vehicle cost.

In general, there’s a distinct trade-off between, on the one hand, the direct costs of the vehicle, i.e. the bill of material, the direct labor cost and other costs directly attributable to the individual vehicle, and on the other hand the indirect/overhead costs like depreciation of tooling and specialized equipment, infrastructure, rent and utilities. That means the larger the intended production volume is, the more the OEM can invest in automation and specialized tooling to reduce the direct and thereby the overall cost per vehicle. Whereas the smaller the production volume, the more the common optimum of direct and indirect costs moves gradually towards a more manual production process with lower indirect costs and (much) higher direct costs. But since the lower indirect costs are spread out over much fewer vehicles, the sum of direct and indirect cost per vehicle increases dramatically for smaller production volumes. The probably most obvious example for this logic is the extent to which robots (high indirect but low direct cost) replace human workers (low indirect and high direct cost) but also the use of hard or soft tools for sheet metal stamping and the volume dependency of all sub-supplier components are equally if not more important drivers of cost reduction over production volume.

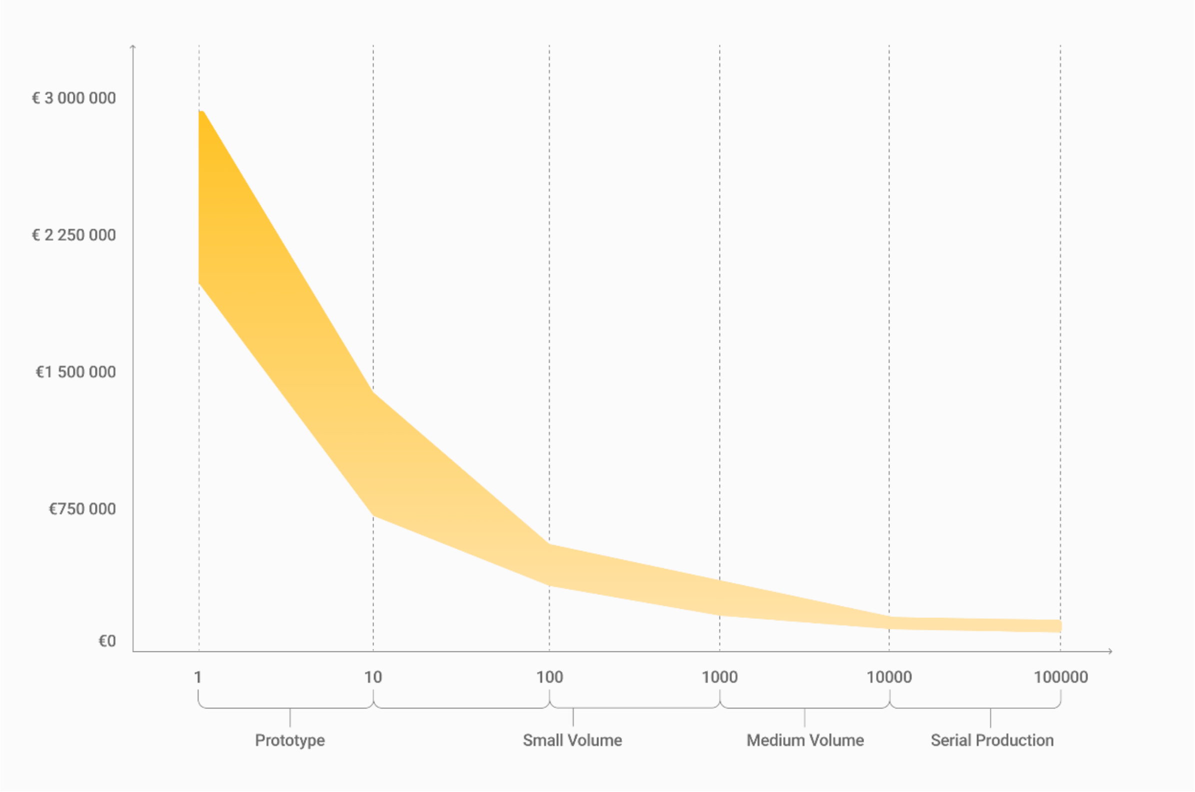

Figure 5-M: Approx. cost over production volume of micro bus type vehicles (Note that the naming of the different production volumes is intended to illustrate orders of magnitude, not hard borders between different production processes. Source: Mobility as a Service AB.

Passenger cars are a consumer product that, as soon as it has received type approval, can be sold to anyone in a very large market. Therefore, the design can be fully optimized for serial production and production can be ramped up as fast as possible as soon as the car is on the market. But since the roll-out of AVs will happen in smaller pilot fleets that operate in limited areas, initial production volumes will be much smaller, and it will take years before annual production volumes of 10 000-100 000 vehicles will be reached. This leaves OEMs with the non-trivial dilemma that, on the one hand, if they develop a vehicle and production process that is optimized for full-scale serial production, the payback period until enough vehicles have been produced is too long. On the other hand, if they optimize the design and processes for the small volume production that is maybe more realistic for the first 2 years of market roll-out, they need to re-do a lot of work for a later ramp-up, and since the customers' expectation concerning vehicle cost is based on experience from serial production passenger cars, it will be difficult to achieve full cost coverage from selling the early low volume production vehicles to fleet customers.

5.10 Investment & financing

A lot has been written about market valuations and fund-raising activities of “pure” AD companies (i.e. companies that focus mainly on the AD software and core hardware components) as the technology is going through the different stages of the Gartner hype cycle, and there are some indicators that it is slowly moving out of the “trough of disillusionment” and into the “slope of enlightenment”, e.g. UK AD company Wayve raising $1 Bn from investors like Softbank, Microsoft and Nvidia[30], the largest ever investment in a European AI company.

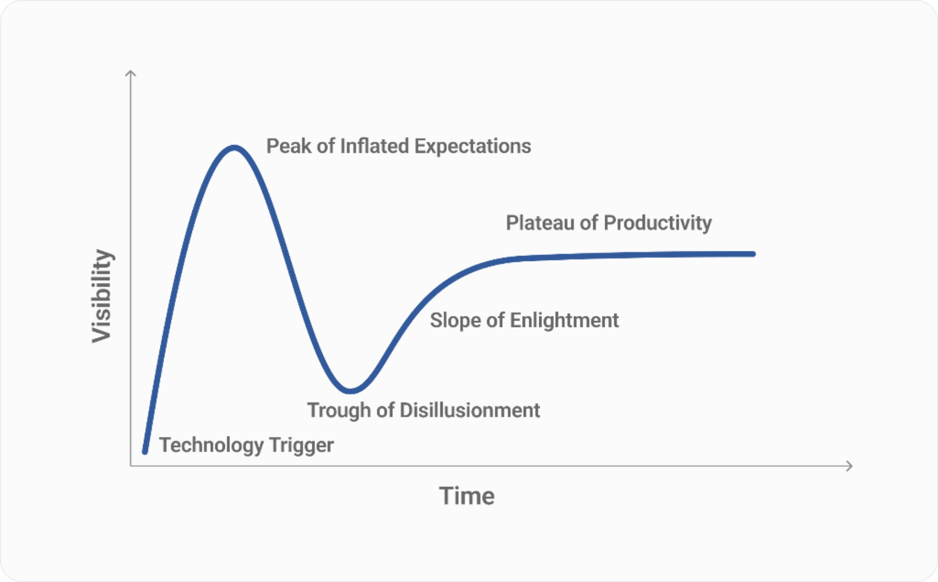

Figure 5-N: The so-called Gartner Hype Cycle. Source: Wikipedia

However, most reporting and discussion evolve around the core AD technology while disregarding the challenges of financing the development of purpose-built serial production autonomous vehicles (or maybe assuming that the required vehicles will simply be available as soon as AD technology has reached the necessary maturity).

AVs are often seen as an opportunity for new players to enter the automotive industry. However, it is extremely difficult to raise the money required for a full vehicle development project from external (non-automotive) sources. The reasons for these difficulties can be found in basic investment characteristics like the overall amount, the relationship of risk and return as well as the time horizon. For most private equity investors (and the authors have met a lot of them trying to find investors for NEVS), the hundreds of millions of Euros required for a vehicle development project are simply too large and even for those that have enough money available to invest, the risk due to a not (yet) existing market and the other challenges described in this chapter is often considered too high. The risk profile would probably be more suitable for venture capital investors, but what makes the investment unattractive for VC is the long development cycle of two years or more followed by a considerable duration until enough vehicles are produced and sold to at least reach break-even.

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[30] SoftBank leads $1 billion funding for UK self-driving startup Wayve | Reuters

OEMs generally finance the development of future vehicles from the operational revenues generated by producing and selling current models and many indirect costs for factory equipment and infrastructure are depreciated over multiple projects. But to many OEMs, the possible upsides of developing and producing Shared AVs are outweighed by the simple fact that their short to mid-term profitability increases with the number of cars they sell, which makes a concept that has small short-term production volumes, and its main long-term promise is to reduce the number of overall vehicles on the roads quite unattractive.

6 Recommendations

The following chapter describes on a high level, approaches to solve and overcome the challenges hindering or slowing down the development and large-scale deployment of shared autonomous vehicles. As described in earlier chapter the largest missing piece of the puzzle is the lack of purpose-built vehicles with the maturity of a traditional vehicle and with the capability of taking out the manual safety driver. This can, only be solved by actors that have the capacity to develop and manufacture such vehicles at large scale, but it doesn´t mean that there are no other pieces that need to be in place. And as the challenges are distributed over different system dimensions, different recommendations are assigned to different stakeholders. For an in-depth discussion of the challenges and their respective backgrounds, please refer to chapter 5.

6.1 Authorities

Most of the recommendations address AD permitting since this is currently the most urgent impediment, but there are also other aspects to consider.

- Take a more pro-active role in the permitting process, particularly in defining the requirements an AV needs to fulfill to be allowed to operate in a specific TOD (refer to 5.6 for a detailed discussion of this topic)
- Focus on Level 4 regulation as it is both the most urgent and has the highest short- to mid-term potential to transform the mobility ecosystem. Define rules that take the non-deterministic behavior of machine learning based systems into account.
- Coordinate regulation regarding fully automated vehicles between countries to meet the requirements of the Commission's implementing regulation (EU) 2022/1426
- As described in 5.6, using regulation and vehicle type classifications that were originally intended for conventional (manually driven) vehicles can result in unforeseen and unwanted difficulties. So instead of working with M1 & M2 rules and allowing individual exemptions when necessary, the permitting process could become more efficient and constructive if one or multiple AV specific vehicle classifications would be introduced. In the UK, there’s an ongoing regulatory initiative to introduce a specific vehicle class for AVs.
- In addition to regulations that ensure that AVs are deployed safely, the market also needs clear (long-term) market rules and regulations around topics like market entry, competition, taxi- and public transportation and tax legislation.

6.2 Public transport and cities

Public transport in general needs to get more involved in the market development so they can affect the technology development and make use of the evolving technology. This includes:

- Take an active role in the discussion, build knowledge about potential usage of services, effects from the services, and what is needed to implement available services as a part of public transport.
- Invest in pilots and early deployments to get things going and start showcasing and explaining to the public what is possible and how these services can be implemented in a safe and transparent way.

- Influence the future solutions by investigating and explaining their optimal usage. Get involved in the development process to understand what is possible and start to define future requirements.
- Create a market by showing a clear vision and roadmap and show potential volumes. Short term by publishing strategy document and long term by tendering these services.
- Create a market by defining a clear position in the value chain. Define what regions, cities, and PTAs will do and not do, so that private actors know which positions along the value chain are available and how they can be addressed.
- Start thinking about how these kinds of services could be tendered in an efficient way leaving room for coordination between fixed line traffic and on-demand solutions.
- Coordination between public actors – PTAs, PTOs, municipalities, transport, and infrastructure authorities

6.3 OEMs

Although it might mean stating the obvious but developing Level 4 automated driving as an add-on functionality for privately owned cars is not a good strategy and will not pay off due to multiple reasons. Firstly, the customer of a privately owned AV will expect the “AD mode” to be available almost everywhere, i.e. the technical and legal challenges for AD to be a real gamechanger in a privately owned car are much tougher than for a mobility service that can work in a much smaller defined area. And secondly, having vehicles not only drive around with a passenger but also empty is almost certain to make the congestion and sustainability problems a lot worse, so rolling out AD technology like that is not in the public’s interest. Furthermore, public actors will likely establish new mobility services in a controlled way, mindful of the general public’s opinion, so deployments will start with small fleets in limited areas before scaling up. So, instead of pursuing AD as an add-on in their existing business model, automotive OEMs should:

- Enter into an active dialogue with public transport authorities and operators (possibly through research projects) to define concrete vehicle concepts, designs and layouts. Setting the specs and requirements right is an iterative process between the service- and the vehicle provider.
- Design the first batch(es) of vehicles to be produced in small series production to allow for changes before ramping up and develop for as much flexibility as possible as late in the process as possible and…
- …embrace small pilot project deployments as an opportunity to learn and to secure a good competitive positioning in the future mobility market, instead of just waiting for a large-scale order that would justify a full-scale serial production.

6.4 AD System providers

Apart from the most obvious recommendation to develop the technology as quickly as possible with as little risk as possible, there are a couple of specific (mainly near term) recommendations that should be highlighted:

- Allocation of responsibility within the safety case is best handled as an eye-level partnership between AD company, OEM, and possibly service operator (if none of AD provider or OEM also act as service operator themselves). The concept of either the AD company or OEM being a tier 1 (or 2) supplier to the other is counter-productive to the (European) permitting process.

- It is understandable that AD companies would like to recover as much as possible of their development costs as early as possible by charging an OEM up-front for vehicle specific development and integration and put as much of the overall commercial risk as possible on the OEM (i.e. act as a tier 1 commercially), and the authors have understood that many AD companies have assumed this in their revenue projections. However, this is not an effective strategy and will most likely lead to delayed commercialization and unhappy investors as it overestimates (in most cases) the bargaining power of the AD company in a negotiation with the OEM. For the detailed allocation of both technical and commercial risks it might worth considering creating a Joint Venture together with the OEM.
- Legal and commercial negotiations as well as technical integration are complex and time-consuming processes that should start as early as possible and need to be given highest prioritization.

6.5 Fleet operators and service providers

The roles of service providers and fleet operator are likely to change and also their relationship to OEMs and AD companies, as well as to PTAs, so:

- Operators need to think about their future role and business model. Their success today depends a lot on how good tools, processes, and competence they have for planning staff and vehicles. What will the business for an operator be when there are no more drivers, planning and routing is automated, and the OEM will take a larger portion of the vehicle operations part?
- Service providers need to think of how they build a modular offer. Looking at the PTA market some actors will probably want to tender a complete solution, but others have their own systems already in place, e.g. travel planner, mobile app, payment, and ticketing.
- Operators and service providers need to work close together with OEMs and AD system providers to define how to exchange data, integrate systems and decide on communication standards to design a system of system that is secure, redundant, and reliable.

6.6 University & research institutes

Academia should support public and private entities in all the points mentioned above, but what the authors think is most crucial and time critical is:

- Help understand and quantify the effects on the whole mobility ecosystem in different use cases and implementations – from implementing shared autonomous vehicles in larger cities to implementing them in smaller communities, semi-urban areas, commuter areas, etc.
- Investigate and put numbers on the indirect and societal effects of different scenarios. What is the societal value of e.g. 10% of commuters choosing to travel with shared services instead of a private car? What is the societal value of e.g. 10% of the elderly can live at home for a longer period of time because of better accessibility? What is the societal value of parents being able to commute to work

more sustainably or kids being able to get to activities without their parents needing to drive them?

- Get engaged and understand tools like agent-based simulation to support both public sector and private actors in general knowledge and interpretation of simulation results.
- Support legal decision makers to understand what legal changes need to be done and how the effects of made decision will look like.
- Support public transport on how public tenders can be conducted in a rapid changing marketplace.
- Support public and private actors in understanding customer behaviour and public acceptance of new technology and new kinds of services.

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