Opportunities, Challenges, and Uncertainties in Urban Road Transport Automation

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Abstract: Automated driving has attracted intense attention in the media and among the general public, based on extremely optimistic predictions from some industry participants, but these have started to become more realistic in the last couple of years, after the “hype cycle” for automation peaked. This paper explains the opportunities for Automated Driving System (ADS) technology to improve the urban transport of people and goods, together with the challenges that will limit the scope and timing of the deployment of urban ADS. The discussion emphasizes the diversity of ADS applications and services, each of which has its own opportunities, challenges, and uncertainties, leading to diverse deployment scopes and schedules. The associated challenges are sufficiently daunting that ADS deployment will lag behind electrification and connectivity, leaving more time for cities to prepare for it.

Keywords: automated driving; road transport automation; autonomous vehicles

1. Introduction—Background on Urban Transport Automation

Urban transport has long been a messy business. Two centuries ago, when cities were significantly smaller than they are today, urban transport was based on human and animal propulsion, with significant adverse environmental implications from the resulting animal-waste products. By the dawn of the 20th century, these were augmented with electrically propelled rail systems and a few self-propelled vehicles using steam engines and internal combustion engines. Common to all of these was the control of the vehicle’s motions by a human operator, the driver.

By 1940, the concepts were already defined and formulated for shifting the driving tasks to an automated driving system, as embodied in the General Motors “Futurama” and Norman Bel Geddes’ book Magic Motorways [1]. Although the initial motivation for automating driving was the comfort and convenience of the user, opportunities for improving traffic flow smoothness, highway capacity and efficiency, and road safety also began to draw more interest.

During the 1950s and 1960s, technology development work began in earnest in the attempts to automate the entire driving task [2,3], while production road vehicles began to incorporate some very limited features to automate specific driving tasks, such as transmission shifting and maintaining a constant cruising speed on highways (“cruise control”). The 1970s saw the first introductions of automated urban people movers on dedicated guideways, sometimes referred to as Personal Rapid Transit (PRT) systems [4], as well as automated urban metros. Automated metro systems and automated guideway transit systems for special applications such as airport terminals have since come into widespread use for high-volume, line-haul transportation applications, but PRT systems have languished because of the high costs of constructing dedicated guideways to serve limited numbers of travelers.

As information technology began to advance more rapidly in the 1990s, interest grew in applying it to automating the driving of a full range of road vehicles, ranging from personal
passenger cars to transit buses and trucks. Public projects in North America, Europe, and Japan demonstrated a wide range of concepts and technologies, and vehicle manufacturers began to incorporate elements of this work into production vehicles in features such as adaptive cruise control and lane-keeping assistance. Now, major vehicle manufacturers and their suppliers, as well as new entrants from the information technology industry, are hard at work developing Automated Driving Systems (ADS) that will take over the dynamic driving task under an increasingly wide range of road, traffic, and environmental conditions. The public imagination has been captured by intensive coverage in the mass media, most of which has been unrealistically optimistic about ADS capabilities and availability. Unrealistic expectations have also permeated much of the technical literature on the topic within the past decade and have been founded more on hopes than on real empirical data. This paper aims to balance the discussion by focusing on the specific real-world transportation applications that could be automated and on the technical challenges and uncertainties that will limit the breadth and timing of the deployment of ADS.

The literature on driving automation is vast, growing rapidly, and obsolescing at least as rapidly. This paper does not attempt to provide a review of the literature as this would be futile. It cites a limited number of key references that provide relevant definitions, or specific, directly relevant, and substantive research findings, or that mark important milestones or turning points in the development of driving automation. The technological, business, and policy environments have changed so rapidly in this field that most of the published works are already obsolete. This applies particularly to the large burst of activity around the peak of the “hype cycle” for automated driving during the past decade, much of which was based on uncritical acceptance of the press releases issued by the companies that have been heavily invested in this field, leading to excessively optimistic assumptions about automation capabilities and the timing for their public availability.

1.1. Terminology and Classifications

The rapid proliferation of activity in the automation of road vehicle driving has led to some level of confusion within the industry and among the general public, pointing to the need for clear definitions of the terminology used to describe the different systems and their capabilities. In order to facilitate clearer communication about the systems and their capabilities, SAE International has published two comprehensive taxonomy and definitions documents [5,6]. The first document, SAE J3016 [5], which has also been published as the international standard ISO 22736, defines the different distributions of functions between the human users and the driving automation systems and has been widely accepted as a document which supersedes many prior attempts to classify levels of driving automation. The second document, SAE J3216 [6], defines the different levels of cooperation among vehicles and between vehicles and the roadway infrastructure. The automation levels [5] are:

- Level 0— No driving automation;
- Level 1— Driving assistance;
- Level 2— Partial driving automation;
- Level 3— Conditional driving automation;
- Level 4— High driving automation;
- Level 5— Full driving automation.

The types of cooperation [6] are:

- Class A— Status-sharing cooperation;
- Class B— Intent-sharing cooperation;
- Class C— Agreement-seeking cooperation;
- Class D— Prescriptive cooperation.
1.2. Automation State of Development and Potential Impacts

The most recent wave of interest in automating road transportation was ignited by the 2010 announcement by Google that it was working (and investing) seriously in this field [7], which led many others in the automotive and information technology world to follow suit. The levels of activity, media attention, and investment followed a classic “hype cycle” pattern, with a peak in the 2015–2016 period, when there were fevered predictions about the widespread deployment of fully automated vehicles by 2020 and the imminent obsolescence of non-automated vehicles. By about 2018, the CEOs of some of the major companies that had already invested at least a decade of effort and billions of dollars in developing automation systems (Waymo [8], GM [9], Ford, [10]) started to issue more cautious public statements indicating that the market introductions would be gradual rather than instant and that it would take decades to achieve deployment in cities across the U.S. The early over-hyped predictions of the very rapid deployment of automated driving, especially those from the financial industry, focused attention only on the demand side of the equation, without paying adequate attention to the supply-side constraints associated with achieving the technological feasibility of safe, automated operations in the face of real-world traffic hazards.

Automation has the potential to produce major contributions toward mitigating multiple urban transportation problems when it is implemented to provide specific transportation services. The automation cannot be viewed as an end in itself but must be treated as a means of providing enhanced transportation services. The potential benefits include:

- Reduced energy use and emissions per VMT by following smooth and efficient speed profiles, especially when coordinated with traffic signal cycles.
- Reduced delays at signalized intersections by using real-time traffic signal phase status updates for coordinated start-up of queued vehicles.
- Increased traffic throughput per lane by safely enabling shorter gaps between vehicles, making more efficient use of road space.
- Potential reductions in crash frequency and severity for vehicles and vulnerable road users (VRUs).
- Increased accessibility of activity centers and transit stations to travelers in low-density areas by making their transit feeder services economically viable through a reduction in labor costs.
- General increase in accessibility for disadvantaged travelers by enabling lower-cost ride-hailing services.
- Reduction in traffic congestion associated with local package delivery by enabling these services to be provided by smaller vehicles that occupy less road space.
- (If automated transit and ride-hailing services mature sufficiently to serve a large fraction of urban trips.) Long-term reductions in private automobile ownership, usage, and space needed for parking.

There are also potential disbenefits to automation in urban transportation, especially if it is not implemented judiciously:

- Employment displacement for people who currently earn their livings as drivers.
- Increases in vehicle miles traveled (VMT) if the costs of travel decline significantly.
- Reduced traffic efficiency if the technology is overcautious in its traffic interactions.
- Reduced traffic safety if the technology is implemented prematurely, before it has been thoroughly debugged.

1.3. Uncertainties

The dominant factor in any discussion of urban transportation automation should be uncertainty because this is a field that is rife with uncertainty. Very little, if anything, is known with certainty at this stage. The scale and timing of the deployments of ADS-equipped vehicles in urban transportation are highly uncertain because of unknowns such as:
How much additional technology development will be needed for the ADS technology to reach sufficient maturity for it to be deployed safely in its initial limited application?

How much further technology development will be needed to extend the ADS technology to each subsequent application?

How much patience will the investors in ADS have in continuing to support their companies’ development efforts before significant revenue streams can be realized?

How well will ADS perform when it is deemed ready for deployment? How safe and with what impacts on traffic system performance?

How comfortable with ADS will the potential customers be, and what will be their level of interest in using an automated transportation service in competition with a non-automated service?

How expensive will ADS be to acquire, operate, and maintain?

What will the attitudes of the general public be toward ADS, and how will that influence public agency decisions about deployment and regulation?

1.4. Overview of Paper

Section 2 of this paper discusses the distinct categories of transportation services that could be automated, beginning with some examples in which automation is already in widespread use and continuing through examples of increasing technical complexity. Section 3 reviews the primary challenges that remain to be resolved before automation can be widely deployed in urban transport (technology safety, remote human support, infrastructure support, viable business cases, and public perception). Section 4 explains the wide range of uncertainties on both the supply and the demand sides of automated road transport, and Section 5 summarizes the potential impacts of automation on traffic congestion, energy use, and pollution. Section 6 provides brief concluding remarks to summarize the contents of the paper.

2. Urban Transport Automation Applications and Services

ADS will be used to take over human driver roles for diverse urban transportation applications and services. Indeed, different cities will have different priorities among these applications and services and different local constraints that are likely to lead them to be deployed in different sequences. Although a great deal of attention is often paid to the differences in the levels of automation that were defined above in Section 1, the Operational Design Domain (ODD) is just as important a factor in determining the feasibility of any ADS application or service. The ODD is the multi-dimensional description of the conditions in which the ADS is capable of operating at its designed level of automation. These conditions that will limit the applicability of any ADS include:

- Geographic location.
- Class of roadway and any relevant physical characteristics of the roadway (pavement surface and marking conditions, grade, curvature, shoulders, lane widths, ...).
- Traffic control devices (signage, signals, tolling, access controls, ...).
- Digital infrastructure (vehicle-to-anything (V2X) communication, GNSS and differential correction availability, map databases, real-time cloud information availability ...).
- Lighting conditions (day, night, dawn, dusk, glare, low sun angles).
- Weather conditions (precipitation, temperatures, wind speed and direction, ...).
- Visibility conditions (obscurants such as dust, smoke, fog, ...).
- Electromagnetic interference environment.
- Traffic conditions (local traffic speed and density, coexistence with VRUs and animals, ...).
- Illegal and reckless actions by other road users.
- Special situations (work zones, incident sites, emergency vehicles, officers directing traffic, ...).

The potential urban transportation applications of automation are discussed here by category in an approximate estimated-deployment sequence (from already deployed to the longest-term future deployment):
2.1. Existing Automated Urban Transportation Systems Already in Widespread Use

Automation is already being widely applied to fixed-guideway transit systems in many cities and has been in use in some cases since the 1970s [4]. These are primarily urban metro systems operating with steel wheels on steel rails, but there are also some systems that drive using rubber tires on paved surfaces, with a variety of different approaches to steering and switching paths. The vehicles generally do not have drivers onboard, but their operations are monitored by supervisors at control centers. The most important distinguishing feature of these systems is that they operate on dedicated and physically segregated tracks, where they do not need to interact with any other vehicles or road users, making this the simplest of ODD situations. Potential unplanned interactions are minimized, for example by the use of platform doors that prevent people and debris from getting onto the track in the path of the vehicles. The dedicated and protected infrastructure is expensive, which is why these are typically applied only to high-volume sites and line-haul routes. The tradeoff is that the automation technology can be much simpler than what will be needed to interact safely with other road users.

2.2. Automated Buses on Dedicated Busways

Some cities that have not been able to afford totally segregated rail transit rights of way have instead decided to build partially segregated busways with their own rights of way (Pittsburgh, Adelaide, Essen), shared with rail transit rights of way (Essen) or in parallel with the general road traffic, with at-grade crossings (Eindhoven, Bogota, Sao Paulo, Curitiba). These busways are candidates for the early applications of ADS on buses as the busway constraints simplify the ODD. The ADS technology can relieve the driver of the lower-level driving tasks to focus more on serving the needs of the customers or may potentially allow for the elimination of the driver to save operating costs (while recognizing that some of the drivers could still be employed to provide remote support for the bus ADS when it encounters a complicated situation).

The busways with their own rights of way can generally exclude other vehicular traffic from encountering their buses, but they cannot generally prevent bus passengers from interfering with the movements of the buses when they board or alight (unless they use innovative station designs such as those in the Curitiba BRT system [11]). The more challenging interactions occur where the busways intersect with other vehicular traffic at grade. Drivers of other vehicles often try to bypass congestion in the general-purpose lanes by intruding into the busways, and conflicts at crossing points are unavoidable.

The technical challenges for the ADS increase as the ODDs become less restrictive on interactions with the other road users. The fixed-route infrastructure of the busway provides opportunities for installing infrastructure-based sensing systems to detect the intrusions of other road users into the busway so that the bus automation systems can be alerted to hazards that could be difficult for their own sensors to detect and recognize. Where the busway includes physical separations from other traffic (such as barriers and fencing to separate it from parallel arterial traffic) the locations of potential conflicts can be minimized, which means that extra infrastructure sensors (and potentially reduced bus speeds) would only be necessary at those specific locations.

This is likely to remain a relatively narrow market niche for ADS because of the high costs and the political challenges of providing the dedicated busway physical infrastructure.

2.3. Automated Low-Speed Passenger Shuttle Vehicles on Fixed Routes

The next step up in ODD complexity from the separated busways is represented by the low-speed passenger shuttle vehicles that have been designed to operate on fixed routes but without physical segregation from other road users [12]. Without physical segregation, the interactions with other road users can occur at any time and place. The very limited range and object recognition capabilities of the sensors on the current generation of these vehicles (typically from companies such as EasyMile, Navya, 2getthere, Yamaha, . . . ) require that they be restricted to low-speed operations in places where they do not need to interact with
high-speed traffic. At their current level of sophistication, virtually every application where these vehicles have been evaluated has required the presence of an in-vehicle attendant to manage the situations that exceed the capabilities of the automation technology. Until the technology advances to a level that does not require this level of near-constant human intervention, the business case for these vehicles is dubious (as the labor cost for the person staffing the vehicle must be covered, it would be cheaper to substitute a conventional vehicle with a human driver).

An ISO standard has already been published to govern the basic design and performance of this class of ADS [13], and a second standard is under development to define remote support functions that could be performed by a human located at a control center when the ADS needs assistance (as a potential alternative to the in-vehicle attendant).

Potential applications for these vehicles include providing access to line-haul transit stations in low- to moderate-density urban and suburban areas, providing circulation services within activity centers (office and industrial parks, large parking facilities, hospital and university campuses, entertainment sites, resort and tourist complexes, etc.), and urban pedestrian and shopping center sites.

Although this has been a popular application for development and field testing in recent years, there are questions about its viability at the current low level of technological sophistication. The limited sensor range and the inability to track, classify, and predict the motions of target objects tends to lead to an excess of false-positive braking events and restricts them to low speeds, and the speed limitation restricts them to short trips as well. The small vehicle capacity (typically 6 to 12 passengers, including standees) further limits them to low- to moderate-density locations. Given these challenges, it is likely that as soon as the more sophisticated automated ride-hailing systems achieve technical viability they will supersede this application, providing a wider range of services, and potentially extending to larger-capacity shared ride vehicles for the locations with a higher density of travel demand.

2.4. Automated Sidewalk Package Delivery Systems

One market niche that is already being exploited by several companies is the automated local delivery of small packages by very small vehicles that operate on sidewalks rather than on the roadways. These generally are not legally classified as vehicles and are not subject to most vehicle safety regulations. They are sometimes called “sidewalk robots” or “personal delivery devices” [14], and because of their appearance, they have also been referred to as “beer coolers on wheels”. They are typically so small that they can only carry a single package per trip; so, each delivery is from one origin to one destination, which implies a significant fraction of empty backhaul travel mileage. The most common applications are for the delivery of restaurant meals or small orders of groceries, and they have been popular for serving student needs on and near university campuses.

Limiting their operations to sidewalks rather than using the streets (except at crosswalks) offers a mixture of advantages and disadvantages:

- They are limited to very low speeds, comparable to pedestrian walking speed or less, to be able to coexist with pedestrians on sidewalks.
- They need to interact very closely and politely with a wide range of pedestrian behaviors, from curious, playful children to potentially hostile adolescents to potentially fearful seniors.
- There is no need to meet national government safety standards, but they are vulnerable to inconsistent local government regulations on sidewalk usage.
- There are political sensitivities associated with sharing sidewalk space with pedestrians, users of wheelchairs, and other mobility assist devices and cyclists, especially in cities with politically active interest groups for these classes of mobility advocates.
- In locations with narrow and uneven sidewalk pavements, the interactions with other users of these sidewalks can be difficult (who yields right of way?)
• Post-COVID-19 extensions of restaurant seating to sidewalks further constrains the available space for vehicle operations.
• In snowy areas, sidewalks are often not properly cleared of snow accumulations, potentially impeding access.
• Small vehicles are vulnerable to harassment, vandalism, and theft.
• Small vehicles driving slowly have limited potential to cause injury to VRUs if they are engaged in a crash situation; so, the safety implications are less acute than for other ADS applications.

The vehicles that provide this class of service can help relieve urban traffic congestion and its energy and environmental impacts if they replace the conventional human-driven delivery vehicles or the trips that the customers would otherwise be making to restaurants or grocery stores. They may also be displacing some employment in the local delivery market, although the technology that they use is so elementary that it tends to need a significant level of human support per vehicle (either an attendant walking behind it or a remote supervisor tracking its progress).

It may be challenging to identify the most fruitful intersection between the technical feasibility and the business case within this application domain. The most efficient utilization of vehicles would be achievable in the highest-density urban locations, where many customers would be within a short distance of the businesses that serve them. However, those locations also tend to have the narrowest and most crowded sidewalks and the most complicated interactions with other road users; so, they are the most challenging technically. On the other hand, the moderate-density suburban locations would be considerably simpler for the technology to manage but would require average trip lengths and times to be longer, leading to lower productivity per vehicle.

The sidewalk delivery robots were the focus of the 2021 Dubai World Challenge for Self-Driving Transport, an international competition among companies [15]. Companies from around the world were invited to compete by making presentations about their end-to-end small local package delivery concepts and services and then bringing their vehicles to Dubai for testing on several sample delivery routes. They were required to show the ability to navigate crosswalks; operate in covered areas with limited GNSS signal coverage; recognize the need to avoid a marked construction zone; interact safely with pedestrians ahead of them and crossing their path; avoid hazards such as a scooter falling across their path and a child’s toy rolling across their path; recognize a relevant traffic signal phase for crossing a street; pass over speed bumps; and drive through rainy conditions represented by a sprinkler system. It is notable that the two competitors that shared the first-place award in the competition were the only ones that had already developed ADS for use in full-scale road vehicles. The companies that only specialized in sidewalk robot applications were not able to successfully pass the entire battery of test cases. This has implications for the longer-term development of these applications, which could change from the current concentration of activity in small companies to stronger involvement by the major companies that are developing the more technically sophisticated applications.

2.5. Automated Local Package Delivery by Road Vehicles

Automated local package delivery is an application that received negligible attention until the last few years but has since attracted intense interest. The growing interest in this topic has been motivated by several factors:
• The significant growth in e-commerce for retail shopping, especially involving very large companies.
• The significant growth in home delivery of food and restaurant meals, accelerated by the COVID-19 pandemic.
• The increasing challenges in hiring drivers for delivery services.
• The growing recognition of the technical challenges for automated ride hailing.
• The need for ADS developers to find “low-hanging fruit” applications that can generate revenue more quickly than automated ride hailing.
The multiple technical advantages for local package delivery compared to ride hailing are worth noting:

- With no humans in the vehicle, the vehicle can be designed to be smaller and of a lighter weight than a conventional delivery vehicle and not need space, crash protections, or HVAC systems for personal comfort.
- With no humans in the vehicle, the automated driving system does not need to meet safety-of-life criteria for protecting the vehicle occupants and can prioritize the safety of other road users (especially VRUs) in potential pre-crash situations.
- The automated driving can be performed slowly and very cautiously without making passengers impatient or uncomfortable with the rate of progress toward the destination.
- The automated driving can be designed to be deferential to other road users (very polite), probably making it easier to gain public acceptance for sharing road space.
- The smoothness of the steering and speed control does not need to be as sophisticated as it would be to make passengers comfortable.

Based on arguments such as these, companies across the world are becoming active in this application domain, and one start-up company was even able to attract in excess of USD 1 billion in venture capital investment [16].

2.6. Automated Ride Hailing (Colloquially Referred to as “Robotaxis”)

This application was the primary focus of ADS development efforts for most of the past half-decade, reflecting the intense interest of the ride-hailing companies Uber and Lyft, which would like to eliminate the need to pay their drivers in order to improve their cost structures. This interest has faded somewhat within the past couple of years as the emphasis has shifted more toward goods movement, for several reasons:

- The urban ride-hailing application is one of the most technically challenging to implement because of the complexity of the urban driving environment, the need to achieve a very high standard of refinement in driving behavior in order to satisfy riders, and the need to implement extensive customer support services.
- The companies developing this application have discovered that it does not scale well when transitioning from one location to another because of the extensive additional development work needed to integrate the driving protocols and peculiarities of each new site into their software stack.
- The companies have also discovered that making the transition from automated operations in the relatively low-density modern suburbs of Phoenix to the higher-density urban environment of San Francisco is challenging because of the dramatically increased complexity of the driving environment [17]. Extrapolating from these fair-weather environments to the more challenging weather conditions in snow-belt cities, they should expect a further increase in technical challenges that still need to be met.
- The earlier predictions of very low costs per automated ride (by not having to pay a driver) have come into doubt as the developers have recognized that the ADS technology will be expensive, and the systems will require extensive remote human support to maintain operations under the full range of conditions the vehicles will encounter.
- The COVID-19 pandemic has shifted market interest away from urban commuting and ridesharing and toward local package delivery (which also happens to be technically easier).
- The disruptions of the COVID-19 pandemic have also called the basic ride-hailing market viability into question, particularly as the ride-hailing companies have tried to reduce the subsidies that their investors have been paying toward each ride until now, while seeing demand decline with the price increases.

After accounting for these factors, it is reasonable to expect the rollout of automated ride-hailing services to be gradual and to lag behind the development of the previously discussed services. Although this is potentially a larger market in the long term, it will require extensive investments of time and effort to bring it to technical viability.
2.7. Automated Driving of Private Personal Vehicles

This is the “pot of gold” at the end of the rainbow that initially attracted intense interest from many companies and investors because of the huge size of the private personal vehicle market. However, it is also by far the most challenging application to develop and the one that has the most mixed prospects for its effects on the overall transportation network. Although Level 2 driving automation features have recently become available in many automobile models and some limited Level 3 automated driving features (only for use in low-speed congested traffic on motorways) are on the brink of market introduction in Japan [18] and Germany [19], Level 4 automated urban driving of private personal vehicles remains a remote prospect for several reasons:

- Private vehicle purchasers expect their vehicles to have full functional capabilities everywhere that they want to drive them, but current experience shows that Level 4 capabilities will only be possible in limited locations and under limited conditions for the foreseeable future. It is doubtful that either vehicle manufacturers or private vehicle purchasers will be interested in a “product” that is only usable in a few specific locations under limited conditions. Extending the ODD for Level 4 automation to a large fraction of nationwide or continent-wide driving conditions is likely to be a slow process and for the long term (on a time scale of decades rather than years).

- The cost of equipping a vehicle with the level of redundancy in safety-critical sensors and actuators that would be needed to meet relevant safety criteria will be very high for the foreseeable future. This makes it economically unjustifiable for personal vehicles that are only used a few hours per day on average, although it might fit into the narrow niche of ultra-luxury specialty vehicles for a handful of extremely wealthy individuals.

- It will be hard to ensure proper training and maintenance for the complex and sensitive components that will be installed in the vehicles when they are not under the direct supervision of a professional fleet operations manager.

- Virtually all of the Level 4 systems in development will require remote support by humans to handle unusual situations (“edge cases”), but there is no current business model for such remote functions in the private personal vehicle market, especially considering that these are safety-critical functions with serious liability implications.

- New automobile insurance models are likely to be needed on both the commercial and the state regulatory sides to account for the crash situations that will involve some mixture of responsibility by the vehicle driver/owner, the automation system developer and maintainers, and the operators of the infrastructure support services. When Level 4 automation features become available for use in private personal vehicles, the initial product offerings are most likely to be limited to motorway driving, especially for low-density, long-distance intercity driving, rather than for driving in the more complex urban environments. This means that the often-hypothesized “nightmare” scenarios involving urban travel becoming so cheap and easy that cities would be overwhelmed with additional VMT [20,21] are unlikely to be encountered within the foreseeable future.

3. Necessary Enablers of Urban ADS Deployment

With the exception of the limited examples discussed in Sections 2.1 and 2.4 above, ADS are not yet ready for general deployment in urban areas. A variety of impediments will need to be overcome, as explained below. Some of these will require substantial investments of time and effort; so, the deployment timeline is likely to be lengthy. Although this means that the transportation benefits from ADS deployment will take a long time to be realized, it also gives stakeholders and policymakers ample time to think carefully about how they would like to steer the deployment process.

3.1. Technological Readiness and Safety Assurance

Although a popular theme among ADS developers is the claim that their technology is ready but they need to wait for the regulators to catch up, this is false in most cases (for all but the simplest systems). The technology is not ready yet, especially with regard to
the ability to ensure safety for all road users when the ADS is in operation. Each ADS needs to be designed to meet the operational requirements for its intended transportation service within its intended ODD. Several major technological challenges remain before safe operations can be achieved in general (unprotected) urban environments:

- The development of the suite of sensors and their associated sensor fusion software to detect, recognize, and track the motions of all objects in the driving environment that could endanger the ADS host vehicle or could be damaged by the host vehicle in the event of a crash. This requires multiple sensors using different physical principles to make them robust with respect to adverse environmental conditions and potential cyberattacks [22]. Some traffic hazards, such as negative obstacles (potholes) and flooded areas, pose challenges for all of the current perception technologies, especially in vehicles driving at highway speeds.

- The development of the software to reliably predict the future motions of all moving objects in the driving environment so that the ADS can take pre-emptive actions (like a defensive human driver) to avoid potential crashes. This is necessary in order to minimize both false-positive and false-negative ADS responses (avoiding unnecessary evasive maneuvers in benign situations and ensuring appropriate evasive maneuvers when it is necessary to avoid crashes).

- The development and implementation of efficient software verification and validation (V&V) procedures for all safety-relevant ADS software. The current state of the art in software V&V is inadequate to this task because of its extreme labor intensity and high costs, which do not scale well from its aerospace origins to the more challenging environment of driving on urban streets.

- The development of a complete safety case to provide sufficient evidence that the ADS will be safe enough to be placed in public service [23]. This is the most fundamental challenge to the general deployment of ADS. It is likely to require extensive international cooperation to marshal the needed expertise and resources to develop the safety case framework, which will need to include:
  - Stakeholder outreach to gain consensus on the safety requirements (how safe is safe enough) and the relevant metrics to use to assess safety.
  - Documentation of the engineering processes that were used to identify and mitigate hazards throughout the ADS development process.
  - Determination of the appropriate blend of methods used to measure the safety-relevant performance of the ADS, combining closed-track testing, public-road testing, and computer simulations (as well as the technical approaches and criteria for validating the simulations to a satisfactory level of fidelity).
  - Documentation of the results of the performance assessments and the engineering processes in forms that will be understandable and acceptable in order to earn the trust of three important but very different audiences: corporate risk managers, government safety regulators, and the general public (and media).

3.2. Remote Human Support

The most experienced ADS developers have recognized, after large investments of time and effort, that they cannot expect the ADS software to be able to manage every situation that it encounters. Although that was the original goal, it became painfully evident that it was not achievable because of the essentially infinite variety of anomalous conditions that the ADS will encounter in real-world traffic. Although each specific condition may be extremely rare, when taken together the sum of these many, many individually rare conditions cannot be disregarded. This is going to require occasional human interventions in the operations of even the most highly automated vehicles that normally operate without drivers. Virtually all of the most advanced ADS developers have remote human support functions incorporated into their system designs, although they are generally loath to mention this in public because it conflicts with the public image of “driverless” operations.
The remote support functions normally take the form of supplementary information or advice that a remotely located human communicates over a wireless link to the ADS. This type of remote assistance is normally offered when the ADS requests assistance because it has encountered a situation that it does not understand or a situation to which it does not know how to respond. The remote assistant would access a data feed from the ADS cameras, microphones, and other sensors and potentially from additional infrastructure-based sensors at locations that are known to be challenging so that he or she could diagnose the situation and recommend a course of action to the ADS. This could be in the form of supplying new waypoints on the ADS route, recommending a detour to avoid an obstructed route, temporarily authorizing a violation of a normal rule of the road (such as crossing a double line to drive around an obstacle blocking the lane), or responding to a police officer’s verbal or gestural cues so that the ADS can resume its performance of the dynamic driving task. This type of remote assistance requires robust and low-latency two-way communication and a high-fidelity user interface for the remote assistant.

A more challenging and controversial form of remote support involves remote driving, in which the remotely located human would temporarily take active control of the speed and/or steering of the ADS-equipped vehicle. This places significantly more demanding requirements on the communication link and the remote driver’s user interface, and at this point there is considerable uncertainty about whether this can be accomplished safely under any but the simplest and lowest speed conditions.

3.3. Supporting Physical and Digital Infrastructure

When ADS developers were primarily focused on the concept of an ADS for private personal vehicles that could be driven anywhere by their owners, they tried to make their ADS operations independent of any special supporting infrastructure (because the ubiquitous availability of such infrastructure could not be assured). This mindset has been slow to change even while the focus of ADS development has shifted toward location-specific implementations to serve specific needs. When it becomes clearer that virtually all ADS implementations within the coming decade will need to be location-specific, the supporting infrastructure will look much more attractive because it only needs to be provided in the specific locations where the ADS service is being deployed. The supporting infrastructure may be physical or digital or both.

Examples of the physical supporting infrastructure include:

- Clear, high-contrast pavement markings;
- Signs that can be readily recognized by computer vision systems (static and variable messages);
- Supplementary illumination to improve visibility in challenging locations;
- Roadside landmarks as localization points of reference;
- Dedicated, and potentially physically segregated, lanes for exclusive use by ADS vehicles;
- Barriers and fences to segregate ADS vehicles from other road users;
- Roadside sensors and communication devices to transmit supplementary information to the ADS.

Examples of the digital supporting infrastructure include:

- Digital maps of varying degrees of detail;
- Real-time traffic signal phase and timing information from the local traffic signal controller;
- Differential correction signals to support GNSS localization;
- Location-specific traffic control information (such as variable speed limits);
- Alerts about location and status of events, such as work zones, crashes, and other incidents;
- Dynamic alerts about time-of-day changes to traffic rules such as lane access restrictions;
- Longer-range traffic condition information from traffic management centers.

3.4. Matching Business Cases against ODD Restrictions

It will only be practical to deploy an ADS-driven application in locations where two fundamental conditions can be met: (a) there is sufficient demand for that application
to support a profitable business, and (b) the ADS is capable of performing the complete dynamic driving task (i.e., its ODD limitations are not violated). It can be challenging to find locations where both conditions are satisfied. Generally, the most profitable business cases are associated with the locations that have the highest density of demand, which also translates into the most complicated operating conditions for the ADS. While the ADS technology is still maturing, the only technically feasible deployment sites are likely to be in less complicated locations that have limited profit potential or can only be served by the most elementary services (such as local package delivery). This consideration is likely to limit the rate of proliferation of the more complex services such as automated ride hailing.

3.5. Public Perceptions of ADS Safety and the Implications for Regulatory Approvals

Public opinions regarding the safety of road vehicle automation vary widely in different locations and among different population groups, which makes it hard to discern whether there is any well-formed consensus view [24–26]. Media reporting tends to emphasize the extreme situations and perspectives (either the fatal crashes or the most optimistic predictions of proponents), which contributes to the volatility of opinion. The general public also does not have an accurate perception of the real-world risks, which leads to divergences between the actual and the perceived risks (consider fear of flying, for example). Industry advocacy groups tend to understate the actual risks, while some transportation safety advocacy groups may tend to exaggerate the risks. These considerations point toward the need for a concerted effort to educate the public about the actual risks associated with ADS usage, based on assessments by impartial organizations that can earn and retain broad public trust.

This is an area in which carefully formulated government safety regulatory standards, in combination with sufficient open disclosure of the safety data by the ADS developers, can provide a trusted “seal of approval” to convince a wide range of stakeholders that the ADS is “safe enough”. Government approaches to vehicle safety regulations vary significantly across countries; so, a single common regulation will not be feasible, and the levels of public trust in government agencies also vary widely. In some countries, the assessments by consumer-focused organizations or independent safety experts may carry more weight with public opinion than government regulatory approvals.

The combination of these factors indicates the relative immaturity of automated driving, especially when compared with the parallel technologies of electrification and connectivity. We should expect to see widespread urban use of electrification and connectivity well before we see a comparable deployment of urban ADS. This provides more time for the ADS developers to build their safety cases and interact with their stakeholders, while the primary near-term deployment focus is likely to be on electrification and connectivity.

4. Managing Uncertainties in Deployment of Automation

Consideration of the deployment of urban transport automation must of necessity be dominated by recognition of the major uncertainties that surround most topics associated with automated driving. Decision making by organizations in both the public and private sectors needs to be conditioned on these uncertainties and with conscious thought about the sensitivity of outcomes to variations in the uncertain decision inputs. Sensitivity studies need to be performed to estimate how much the outcomes change when the input assumptions vary between optimistic and pessimistic values so that “minimum regret” decision options can be emphasized.

The uncertainty factors can be clustered into two broad categories: (a) the combination of the ADS technology, the supporting infrastructure, and the business case that determines the “supply side” feasibility of implementing an ADS-based urban transportation service on one hand and (b), on the other hand, the “demand side” combination of regulatory agency and general public acceptance that determines how receptive an urban area is likely to be to the deployment of the ADS-based service.
4.1. Supply-Side Uncertainties

Assessment of these uncertainties is challenging because information about the true state of the development of ADS technology is very closely guarded within the companies doing that work. Their public statements on these topics within the past decade have largely proven to be seriously over-optimistic; so, it is necessary to factor that bias into an estimation of the real state of affairs.

1. How do the ADS sensor perception and hazard recognition capabilities compare with human capabilities, and what does that signify in terms of ADS safety? These capabilities already vary significantly among different ADS implementations. The simple, low-speed shuttle vehicles only detect the presence of objects in their vicinity, without identifying what they are, tracking their motions, or predicting their future motions; so, they are far inferior to human capabilities. This means that the vehicles need to be programmed based on very conservative estimates of those unknowns, leading to high frequencies of false-positive stopping. This reduces their productivity and efficiency and produces passenger discomfort. Even the most sophisticated prototype ADS vehicles currently display a performance that is similarly cautious to new-learner drivers or elderly drivers with reduced perceptual capabilities (e.g., false-positive stopping for pedestrians standing on the roadside and extra-long stopping times at stop signs).

2. How extensive (and expensive) a combination of environment perception sensors will be needed to provide the ADS with sufficiently robust perception capabilities? The current trend among the most experienced ADS organizations developing Level 4 automation systems indicates the need for multiple complementary sensors using different physical principles (machine vision + lidar + radar + precise localization/mapping + V2X communication) to provide robustness against cyberattacks [22] and environmental conditions that could impair the effectiveness of any of these individual sensor modalities. When these multiple sensor technologies are applied to provide 360-degree coverage around the vehicle, the device count and costs become large, pointing toward a very high vehicle capital cost. This has implications for the economically viable use cases, which will most probably need to be in commercial fleet operations that can keep the vehicles productively occupied for many hours per day and that can justify the high vehicle costs based on significant savings in driver labor costs.

3. How extensive a process will be needed to provide adequate assurance of ADS safety to satisfy corporate risk managers at the ADS developing company, government safety regulators, and the broader public safety stakeholder community? Although this is a subject of intense interest, there is no convergence yet on an answer to this question. The process is likely to vary across countries that have different societal tolerances for risk, but it appears that it will be necessary to include at least the following elements:
   a. Outreach to public stakeholders to seek consensus on relevant safety metric(s), reference safety baseline(s) for comparison, and acceptable ADS safety level(s).
   b. Documentation of a safety-conscious ADS design process, at least showing how functional safety [27] and the safety of the intended functionality [28] requirements have been addressed.
   c. Technical demonstrations of safety-relevant ADS performance using some combination (still to be determined) of naturalistic public road testing and the testing of specific safety-critical scenarios on closed test tracks and in computer simulations. The processes for selecting the required scenarios and for validating the simulations are not defined yet.
   d. Presentation of the results of (b) and (c) to the safety regulators and the public stakeholders in ways that they can be readily and correctly understood and trusted by non-technical audiences.

The costs and schedules associated with these processes are still highly uncertain.
4. **What kind of supporting infrastructure, especially with segregation from other road users, is likely to be available to augment the in-vehicle ADS capabilities?** If more extensive infrastructure support is available, the in-vehicle ADS technology could be less complicated and costly; so, its deployment could potentially be faster and cheaper. However, it is much more expensive and difficult to construct new roadway infrastructure in existing built-up cities than it is in new cities that are being developed in greenfield or brownfield environments. The level of political and financial support that will be available for investing in significant public infrastructure enhancements to facilitate ADS operations in existing cities is highly uncertain.

5. **How extensive are the private investments needed to extend ADS operations from their first well-established location to other similar locations and to additional dissimilar locations?** Recent indications from early ADS prototype testing on public roads imply that significant efforts are needed in developing detailed maps and in learning the location-specific driving behavior protocols that are needed to coexist safely with other local road users. More knowledge needs to be gained on this subject in order to understand how much time and effort will be needed to expand ADS operations to additional cities with similar characteristics to the initial host cities, as well as to the cities with more challenging traffic and weather conditions.

6. **What density of transportation service demand (for freight and passenger services separately) will be needed to support viable business cases for ADS deployment?** This is a central uncertainty for the expansion of ADS services beyond their initial prototype deployments, where their developers will need to heavily subsidize the rollout of the services. There have already been early indications that the suburban locations in Arizona and California where Waymo and Cruise have been doing much of their initial technology development testing may not have sufficient density because these companies have shifted focus toward the higher density (and much more challenging traffic conditions) of San Francisco for the introduction of commercial revenue operations. Table 1 compares the population densities of these locations with the densities of a couple of representative major European cities to provide an international perspective:

| City               | Density (Population Per Square km) |
|--------------------|-----------------------------------|
| Chandler, AZ       | 1800                              |
| San Francisco, CA  | 7200                              |
| Berlin, Germany    | 4200                              |
| Paris, France      | 20,000                            |

While the higher density of San Francisco should provide a significant advantage in terms of operational efficiency, trip density, and reduced empty backhaul mileage percentage, Table 2 shows the large difference in the complexity of the traffic challenges that it poses for the ADS technology, based on the data published by General Motors/Cruise [17]. It is particularly noteworthy that the more complex events, which are the most challenging for ADS, occur at a dramatically higher frequency per mile of automated driving in the higher-density San Francisco environment than in the unnamed suburbs of Phoenix (by a much higher ratio than the 4:1 ratio in population density).

7. **If the ADS vehicles are operating in an automated ride-hailing service that requires them to deadhead between revenue-service trips, how much of an increase in non-revenue VMT and its associated negative efficiency and environmental impacts does that require in different operating environments?** The trip origin–destination patterns can vary significantly across cities and with respect to the time of day within any given city. These can have significant impacts on the excess deadheading VMT the operator incurs in delivering the service. The data from existing ride-hailing services in major U.S. urban areas
were reported by Schaller [29] to show that deadheading mileage represents between 40% and 50% of the total mileage driven by the ride-hailing drivers, with the lower percentage associated with the higher-density urban core locations and the higher percentage associated with the lower-density suburban and regional operations. If the future automated ride-hailing services were to be used more intensively than the current services, to what extent could these large percentages of unproductive mileage be reduced?

Table 2. Comparison of frequency of occurrence of challenging traffic scenarios in the city of San Francisco and the suburban Phoenix area (Source: [17]).

| Maneuver/Scenario                  | Ratio of Occurrence per Mile in San Francisco vs. Phoenix Suburbs |
|------------------------------------|-------------------------------------------------------------------|
| Left turn                          | 1.6                                                               |
| Lane change                        | 5.4                                                               |
| Construction blocking lane          | 19.1                                                              |
| Pass using opposing lane            | 24.3                                                              |
| Construction navigation            | 39.4                                                              |
| Emergency vehicle                  | 46.6                                                              |

4.2. Demand-Side Uncertainties

The uncertainties on the demand side are more qualitative than the uncertainties on the supply side, but they have similar importance in influencing the potential for the future deployment of urban ADS.

1. **How will the ADS deployments fit into the different safety regulatory frameworks in different countries (UNECE-based third-party type approvals or NHTSA FMVSS-based self-certifications by ADS developers)?** At this point, no safety regulations specific to ADS have been defined within either framework (with the exception of the very limited scope of UNECE R157 for “Automated Lane Keeping Systems” [30]); so, there is limited experience to build on. Within the UNECE framework, each new ADS function will require the definition of a specific regulation with its own technical requirements before that function can be deployed in vehicles. In the NHTSA framework in the U.S., anything is permitted unless an FMVSS regulation prohibits or restricts it, and at this point, NHTSA has not even initiated the creation of any FMVSS regulations specific to ADS. The form of the FMVSS regulations is generally different from the UNECE regulations and, based on the existing NHTSA standards, these are more likely to be defined in terms of generic cross-cutting functionalities or processes rather than specifying design features or performance characteristics for any specific ADS feature. The timing of the development and promulgation of both kinds of regulations is highly uncertain, but it is unlikely to be quick because of the newness and complexity of the issues involved with ADS safety.

2. **How will the public perceive the actual safety and the required safety for ADS applications?** The perceptions of the general public regarding the safety of transportation systems and other technical systems are notoriously divergent from their actual safety. Public perceptions are easily distorted by marketing hype from vendors on one side and by sensationalist reporting on crashes by the media on the other side. This poses large challenges for the ADS developers and for the government agencies responsible for transportation system safety operations and regulations, who will need to learn how to communicate ADS safety information to the public accurately and in ways that can be easily understood and trusted. This is likely to need new and unprecedented levels of public–private and international coordination and cooperation to agree on coherent messages and how to deliver them. Earning the trust of the public and the traffic-safety stakeholder groups is also likely to need a level of openness about the
sharing of safety-relevant data that will be uncomfortable for the ADS developers who prefer to define their competition-sensitive intellectual property very broadly. The development and implementation of strong and technically valid government safety regulations for ADS can also make an important contribution toward earning public trust in ADS safety by giving an official “seal of approval” to the ADS that are successful in satisfying the regulatory requirements.

3. How will the public and their political representatives react to media reports on crashes of ADS prototypes in testing and early deployment? Public attitudes toward ADS are still relatively unformed as very few people have had the opportunity to experience ADS operations in person, and there is very little tangible information available to give realistic impressions to the rest of the population [24–26]. This means that high-profile media coverage of ADS crashes can have an outsized influence on shaping public attitudes at this early stage prior to substantial real ADS deployments. When an ADS crash injures or kills a celebrity or an innocent child, there is a potential for substantial backlash against ADS testing and deployment, which could set back progress toward deployment. The good work of the ADS developers who are being conscientious about safely developing and testing their systems could be undermined by the negligence of any ADS developer who is not paying adequate attention to ensuring safety.

4. How can ADS safety case results be presented to safety regulators, the media, and the general public in a readily understandable and convincing form? The ADS developers face multiple challenges in the safety-assurance process, most of which are technical. However, a vitally important non-technical challenge is learning how the results of the highly technical safety case work can be explained effectively to largely non-technical audiences so that they can have confidence in the results. Earning the trust and respect of these non-technical audiences by providing them with properly convincing evidence of ADS safety will be critical to achieving societal acceptance of the widespread deployment of ADS, and if the safety case results are not explained well, acceptance could be jeopardized.

5. Impacts of ADS on Traffic Congestion, Energy Use, and Pollution

The uncertainties discussed in Section 4 make it challenging to estimate the impacts that urban transport automation will have on key performance measures for transportation systems. The transportation safety impacts of ADS deployment will depend directly on the criteria that safety regulators apply in determining which ADS to authorize for public use. It seems reasonable to assume that regulators would be reluctant to approve ADS that cannot provide evidence that their driving will be at least as safe as typical human drivers operating under comparable conditions; so, some degree of safety improvement should be expected. The actual extent of the safety improvements that can be realized under different operating conditions will remain highly uncertain until significant real-world operational experience can be gained.

The impacts of automation on other key transportation performance measures, such as traffic congestion, energy consumption, and emissions of pollutants, will depend on how the deployment of ADS is coupled with the deployment of electrification and connectivity technologies. There are already strong indications of coupling between automation and electrification, with most ADS technology development focused on vehicles with electric or hybrid powertrains. California has already passed legislation requiring that automated light-duty vehicles be zero-emission [31], and there are good technical reasons for focusing ADS deployment on electrically propelled vehicles (the availability of ample electric power for sensors, computers, and actuators, the ease of installing additional electrical components and subsystems, and simpler vehicle dynamics). Electrification will have the dominant effect on the energy and environmental measures of effectiveness, but connectivity will be the dominant influence on the congestion-related measures. The interaction between
connectivity and automation has a strong effect on congestion at high market penetration, but the effects are small at low market penetration.

Recent research has shown that automation without connectivity is likely to make traffic congestion worse (with associated adverse effects on energy consumption and emissions), but automation with connectivity will facilitate traffic flow (at comparable traffic-demand levels). The physical reasons behind this include:

- ADS software is designed to drive cautiously for safety reasons, to compensate for the limited perceptual and predictive capabilities of unconnected ADS compared to that of humans; so, it leaves larger gaps when following other vehicles or changing lanes, stops longer at stop signs, proceeds more gradually when traffic signals turn green, and is more deferential to VRUs in its vicinity.

- When the ADS is combined with V2X communication, it can negotiate close but safe lane change and merging maneuvers with other vehicles; it can anticipate traffic signal phase changes based on the data communicated directly from the traffic signal controllers; and it can exchange information directly with the VRUs so that each can anticipate the motions of the other. These capabilities can enable cooperative ADS to improve traffic conditions compared to baseline human driving.

- In car-following maneuvers, the ADS sensors concentrate on the immediately preceding vehicle(s) rather than considering traffic conditions several vehicles ahead; so, they do not take advantage of the preview information that experienced drivers use to anticipate and compensate for shock waves in traffic. This makes their car-following behavior less stable and more inclined to amplify traffic disturbances.

- When the ADS is augmented with V2V communication, it can form closely coupled platoons, using anticipatory information about the motions of multiple preceding vehicles, enabling significantly shorter gaps with stable vehicle following to damp out shock waves.

These effects have been measured in full-scale vehicle experiments [32–35] and the results of those experiments have been incorporated into simulation models to predict the broader implications when many vehicles are equipped with ADS, with and without V2X communications [36,37].

6. Concluding Remarks

During the period of maximum hype about the imminent widespread deployment of ADS over the last five years, a variety of researchers and environmental advocates predicted “nightmare” scenarios in which the volume of vehicular traffic would surge ahead, producing a significant worsening of traffic congestion and its energy and environmental impacts [36,37]. Based on more sober consideration of the challenges to ADS deployment and the resulting likelihood that it will lag significantly behind electrification and connectivity, the “nightmare” scenarios look increasingly improbable now. The ADS technology will be applicable to relatively narrow segments of the vehicle fleet for the foreseeable future (only to provide specific transportation services in specific geographic locations). By the time it has matured to the level that it will be technically and economically viable for application to the vehicle mass market of many millions of vehicles, those vehicles will have already been electrified and equipped with connectivity. The combination of automation with connectivity and electrification offers opportunities for improving transportation sustainability.

The field of road transport automation is still in its infancy, with many fundamental research questions remaining unanswered. Opportunities abound for future research to resolve many of the current uncertainties and to remove the technological impediments to the widespread safe deployment of automated road transport. These will provide ample work for multiple generations of researchers. Extensive research is needed to develop the methodologies and policy framework for the safety assurance of ADS [23] and, at a more fundamental level, to develop efficient and scalable methodologies for developing, verifying, and validating safety-critical software. Major research and development efforts
are needed to develop more capable environment-perception sensors and sensor fusion systems to provide ADS with the ability to detect, recognize, and understand all the relevant safety hazards in the driving environment. Existing research efforts need to be augmented with extensive real-world data collection on the performance of ADS and their interactions with other road users in order to support realistic predictions of the traffic, energy, and environmental impacts of ADS deployment in different transportation applications and at different market penetrations. This needs to include extensive efforts to understand public attitudes toward ADS and how those will affect consumer decision making and public policy in the future.

This paper has provided an overview of the real potential that automated driving has for changing urban road transport. It has identified the challenges as well as the opportunities, offering a less optimistic view of the topic than most writings of the past decade, but, in the view of the author, a more realistic view. The dominant consideration in this is uncertainty, based on the real limitations in current capabilities and understanding that will need to be overcome by the coming generations of researchers.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The author declares no conflict of interest.

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