

The Impact of Autonomous Vehicles on Future Cities

How Best to Ensure AV Success

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Abstract

Since the beginning of urbanization, mobility has been a prevailing issue in cities and a key driver of growth and progress. Today's transport networks, however, are reaching their limits, resulting in high levels of congestion, many road traffic deaths, high levels of pollution, and overconsumption of public space. Autonomous vehicles (AVs) are widely considered as one technology potentially able to initiate a major change in mobility in order to improve traffic conditions. Yet achieving this goal requires profoundly understanding how AVs impact cities and thus make this technology a success.

This dissertation comprises four articles. Together, they explore the threats of and the opportunities for AVs in future cities. They offer recommendations on maximizing the benefits of AVs while minimizing their negative effects. They provide state-of-the-art research and, by approaching AVs from various angles, make suggestions that will hopefully be relevant for future political discussions and practice.

Article 1 establishes the current state of knowledge about how AVs impact cities based on a literature review. Its insights into the uncertainty about predicting the impact of AVs in the literature pave the way for the other three articles. This article also proposes various drivers of AVs and how they impact its success. It suggests how policymakers might positively influence the implementation of AVs.

Article 2 performs a macroscopic simulation to assess which type of AV has the greatest positive effect depending on the urban structure. It is the first attempt to explore the impact of AVs on a large scale across different megacities. The study highlights that not all cities benefit equally from AVs. Whereas shared AVs have advantages, privately-owned ones do not.

Article 3 assumes that shared AVs offer the greatest advantages for cities. These benefits, however, exist only if operators consider this kind of service to be financially viable. A microscopic simulation was conducted in Zurich, Switzerland to determine the profitability of an AV service depending on fleet size. Several recommendations are proposed for improving the shared AV business model.

Article 4 offers strategic insights into what might make AV a corporate success. The article shows that managers need to analyze how different AVs could create value for different cities. It also suggests how managers might best prepare for the future.

Zusammenfassung

Seit Beginn der Urbanisierung ist die Mobilität ein wichtiges Thema in den Städten und ein bedeutender Treiber für Wachstum und Fortschritt. Die heutigen Verkehrsnetze stoßen jedoch an ihre Grenzen, was zu Staus, vielen Verkehrstoten, einer hohen Umweltverschmutzung und einer Überbeanspruchung des öffentlichen Raums führt. Autonome Fahrzeuge (AVs) sind Technologien, die potenziell in der Lage sind, eine Veränderung der Mobilität einzuleiten, um die Verkehrsbedingungen zu verbessern.

Diese Dissertation umfasst vier Artikel. Gemeinsam zeigen sie die Bedrohungen und Chancen für AVs in zukünftigen Städten auf. Sie bieten Empfehlungen zur Maximierung der Vorteile von AVs bei gleichzeitiger Minimierung ihrer negativen Auswirkungen. Sie liefern durch die Betrachtung von AVs aus verschiedenen Blickwinkeln Vorschläge, die für künftige politische Diskussionen und die Praxis relevant sein werden.

Artikel 1 stellt auf der Grundlage einer Literaturrecherche den aktuellen Wissensstand fest, wie sich AVs auf Städte auswirken. Die Erkenntnisse über die Unsicherheit bei der Vorhersage der Auswirkungen von AVs ebnen den Weg für die weiteren Artikel. Anhand von verschiedenen Faktoren wird gezeigt, wie politische Entscheidungsträger die Einführung von AVs positiv beeinflussen können.

Artikel 2 führt eine makroskopische Simulation durch, um zu beurteilen, welche Art von AV je nach Stadtstruktur den größten positiven Effekt hat. Es ist der erste Versuch, die Auswirkungen von AVs in verschiedenen globalen Megastädten zu untersuchen. Die Studie macht deutlich, dass nicht alle Städte gleichermaßen von AVs profitieren. Während gemeinsam genutzte AVs Vorteile haben, bieten privat betriebene AVs weniger Nutzen.

Artikel 3 basiert darauf, dass gemeinsam genutzte AVs die größten Vorteile für Städte bieten - jedoch nur, wenn das Betreiben der Flotte rentabel ist. In Zürich (Schweiz) wurde eine mikroskopische Simulation durchgeführt, um die Rentabilität eines AV-Dienstes in Abhängigkeit der Flottengröße zu bestimmen. Empfehlungen zur Verbesserung des Geschäftsmodells werden aus den Ergebnissen abgeleitet.

Artikel 4 bietet strategische Einblicke, wie AVs zu einem Unternehmenserfolg beitragen. Der Artikel zeigt, dass Manager analysieren müssen, wie verschiedene AVs einen Mehrwert für unterschiedliche Städte schaffen können. Außerdem wird gezeigt, wie Manager sich am besten auf die Zukunft vorbereiten können.

Introduction

Today's cities require transformation. In the last century, policymakers encouraged car-centric cities since privately owned vehicles were associated with greater prosperity and economic growth (UN Habitat, 2013). As a result, people living in cities such as Bogota spend up to 272 hours a year in traffic (INRIX, 2019). London recorded 110 road deaths (Transport for London-TFL, 2019). In Barcelona, Hong Kong, and New York, traffic infrastructure (e.g., roads and parking spaces) occupies more than one third of public space (UN Habitat, 2013). Policymakers face the major challenge of reshaping cities by implementing new mobility solutions capable of counteract today's traffic challenges. One key question is: Can autonomous vehicles (AVs) positively influence 21st-century city traffic?

In recent years, autonomous driving has become a reality. Companies such as Waymo and NuTonomy launched self-driving-car-services already in 2016. According to Bloomberg (2019), there are 24 AV pilot projects in the US and 50 other pilot projects across the world. If such companies expand their services from suburban pilot projects to area-wide operations in cities around the world, a fundamental revolution in mobility is likely to occur, as well as a dramatic change in traffic, urban form, and travel behavior. AVs will come in different forms and type of use (Boesch et al., 2018). AVs can be privately owned or offered as an on-demand service by a fleet provider. Figure 1 shows three types of AVs.

AV-Pod	AV-Taxi	AV-Shuttle
		
Seats: max. 2 passengers Operation: on-demand service / privately owned	Seats: max. 5 passengers Operation: on-demand service / privately owned	Seats: max. 15 passengers Operation: on-demand service

Fig. 1.: Types of autonomous vehicles considered in this dissertation (Source: Daimler (2020), nuTonomy (2019), eGo Moove (2020)).

AVs have the potential to fundamentally alter transportation systems and to achieve far-reaching positive effects. AV deployment could reduce pollution in urban areas (Brown et al., 2018), lower the demand for parking spaces (Yi et al., 2018), improve safety

(MacKenzie et al., 2014; Clements & Kockelman, 2017), and reduce transport costs (Boesch et al., 2018). However, these potentials of autonomous driving can only be unlocked if the effects of AVs on cities and their populations are understood and if implementation is systematically controlled. If, however, AVs are deployed merely as upgraded human-driven vehicles, the optimal benefits of this new technology may not be achieved, especially in large metropolitan areas with high population densities and limited road resources (Shen, 2018). Rather, an uncontrolled introduction of AVs might significantly deteriorate traffic conditions and, even more seriously, social conditions within cities (Milakis et al., 2017). This raises the question: How best to ensure that AVs are successful?

Although AVs currently still need to overcome several technical challenges, many studies conclude that AV success is mainly influenced by policymakers, who significantly shape the impact of AVs (Anderson et al., 2014; Clark et al., 2016; Enoch, 2015; Fox, 2016). For example, policymakers could use licenses to decide which companies may enter the transport ecosystem or which criteria must be met to enable introducing AVs. According to some studies, one of the leading risks of AVs is that, if implementation is mismanaged, they will reinforce car dependency, and hence its adverse environmental, health-related, and social consequences (Papa & Ferreira, 2018). Thus, favourable regulation and a framework (i.e. strategic plan) for AV introduction is an essential prerequisite for successfully introducing AVs.

Introduction to traffic simulation methodology

Simulations aim to appropriately represent the environment by modelling a real-world or hypothetical scenario on a computer to facilitate investigation (Lovas, 1994). Changing the variables and implementing different scenarios enables drawing conclusions about their impact on the initial situation. The overall aim, however, is to provide a sufficiently accurate representation of a particular traffic situation under changed framework conditions (Bando et al., 1995). Simulations are used if real-world scenarios are too large or too complex, or take too long or are too costly to observe in direct experiments. To better understand the impacts of introducing AVs in cities, this dissertation devises and examines different scenarios. The basic case scenario represents the current traffic situation. This scenario will account for the initial situation whereas other scenarios represent the basis for a sensitivity analysis, which will lead to calculating the impacts of the newly generated scenarios.

In essence, two different traffic models are distinguished in the literature: microscopic and macroscopic simulation (Hidas, 2005):

Microscopic simulations are mostly agent-based and offer the highest level of detail (Figure 1). Such models depict each individual vehicle and also take into account additional influences (e.g., vehicle interaction, individual characteristics, such as braking or acceleration behaviour, as well as individual characteristics of the traffic environment, e.g., traffic lights). The “human” component is also added as a driver variable. Similar to reality, each agent has a daily schedule with activities to be performed for a certain duration and to be completed at a certain time of day. Since these activities take place at different points in the scenario, agents must switch from activity to activity.

In contrast, macroscopic models mostly follow a non-agent-based approach. This focuses on complete road flow and models traffic flow in an entire network (Figure 2). These models are used for flexible visualizations that enable fast experimentation. The model in general allows testing and comparing multiple city archetypes. The purpose of macroscopic models is to describe large-scale traffic flows. Macroscopic models do not consider every single trip. Vehicle quantity is combined into a total and traffic flow calculations are performed based of this combined vehicle stream (Bhat, 2012).



Fig. 2.: Microscopic simulation model
(Source: VISSIM; PTV AG).

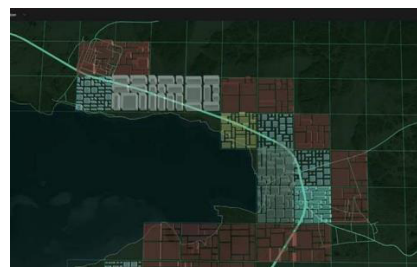


Fig. 3.: Macroscopic simulation model
(Source: BCG Gamma).

Four articles about the impact of autonomous vehicles on today's cities

On the scientific side, this dissertation explores the impacts of AV introduction and its consequences for urban cities. If the effects of AV introduction are already known today, at least along general lines, industry and politicians could prepare for the future such that AVs improve the quality of life in cities and contribute to solving two major challenges: congestion or pollution. A literature review shows, however, that the benefits of introducing AVs are still largely underresearched:

First, most studies using traffic simulations to investigate the impact of AVs are spatially limited to specific cities. Few studies have considered more than one city while simulating the impact of AVs. Comparing the results of recent studies reveals a contradiction in the literature (see Article 1).

Second, most studies to date have focused on a single parameter (e.g., emissions, parking areas, or vehicle volumes). Only a few studies have considered multiple parameters based on simulation results (see Articles 1 and 2).

Third, few studies have provided a comprehensive strategic plan on how cities might best develop a mobility concept for the future. Since many studies have focused on specific aspects, the formulated recommendations make it more challenging for policymakers to gain comprehensive insights (see Article 2).

Fourth, only a few publications have so far analyzed whether operating an AV fleet in urban areas is profitable for operators. Although some studies have attempted to provide insights into the profitability of AV fleets, no study has considered profitability based on a simulation within a European city (see Article 3).

To contribute to the literature on how AVs affect cities and how suitable measures can already be taken today to ensure that AVs achieve the greatest possible benefits, this dissertation is divided into four parts. While each constitutes a paper of its own, they are nevertheless linked. Figure 4 provides an overview of the general structure and conceptual framework of this four-part research project. The underlying focus and methodology involve traffic simulations that have been designed to model traffic volume as a key performance indicator (KPI). In answering its overarching research question — How best to ensure that AVs are successful? — this dissertation considers the views of different stakeholders (e.g., policymakers, fleet operators, and managers in general). The focus is on private transport while freight traffic is excluded. Table 1 shows the individual articles of this dissertation.

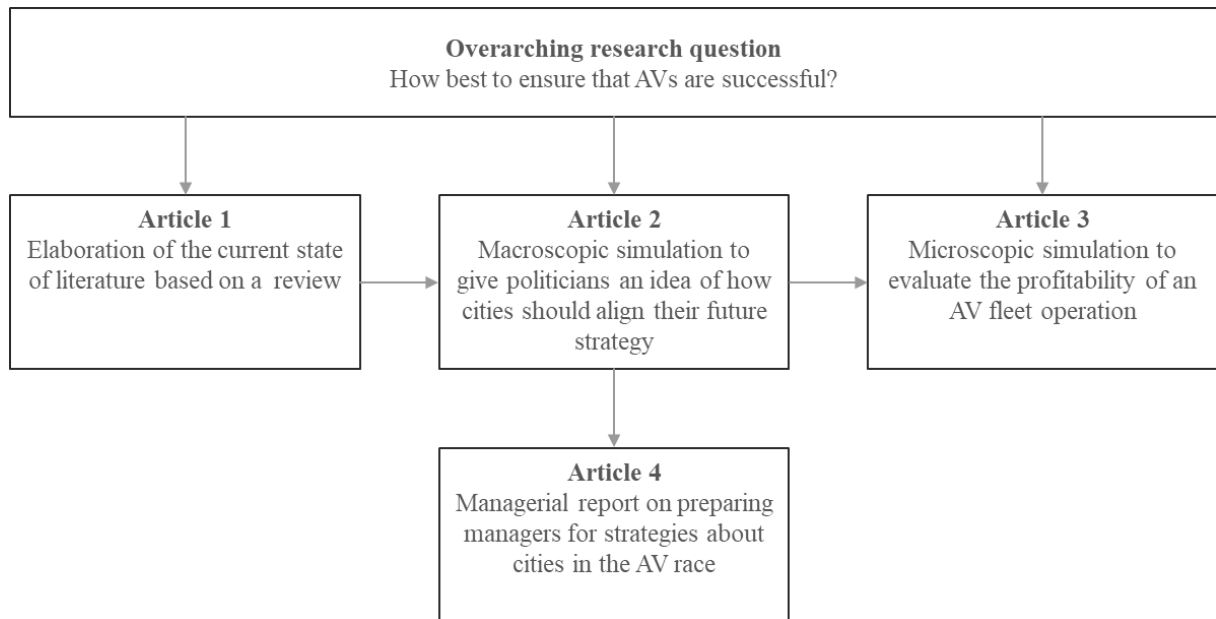


Fig. 4.: Framework of the dissertation based on the overarching research question.

Article 1 reviews the current state of the literature. Through an analysis of over 200 papers, this article identifies the major challenges facing today's cities (e.g., congestion, pollution, etc.) due to car-centric traffic. The findings reveal a contradiction in the existing literature regarding the effects of AVs on cities and traffic. Based on these findings, the article paves the way for Articles 2 and 3 by identifying which factors influence the success of AVs.

Article 2 extends Article 1 by providing an independent macroscopic simulation. By simulating different scenarios of how AVs influence today's cities, the article explores which cities benefit most from AVs, and how policymakers should align their long-term mobility strategy. The results show that not every city will benefit to the same extent from AVs. Nevertheless, shared autonomous vehicles may be said to create the greatest added value for cities.

While articles 1 and 2 mainly look at the effects of AVs from the perspective of cities and politicians, **Article 3** looks at the implementation of AVs from the perspective of fleet operators. A microscopic simulation is carried out in the city of Zurich to provide insights into the profitability of AV fleet operation depending on fleet size. For it is only when AVs prove interesting enough for cities and companies alike that comprehensive implementation and thus the positive impact of AVs on cities can be ensured.

Article 4 builds on the results of the traffic simulation in Article 2 and transfers them to management perspective to provide strategic insights into what needs to be done to

make AV a success. Since this article is targeted at MIT Sloan Management Review it is not considered in the general structure of the dissertation and serves a supplementary purpose.

Table 1

Overview of research project and links between the articles

	Article 1	Article 2	Article 3
Title	Can Autonomous Vehicles Solve Today's Traffic Burden? – A Systematic Literature Review	Assessing the Impact of Automated Vehicles on Cities with Differing Urban Structure	Exploring the Financial Implications of Operating a Shared-Ride Autonomous Vehicle Fleet in Zurich
Author(s)	Maximilian A. Richter	Maximilian A. Richter Markus Hagenmaier Oliver Bandte	Maximilian A. Richter Christoph Baur Raphael Stern
Research question	How best to ensure that AVs are successful?		
	- Which impact areas can be identified that are affected by traffic today? - What drives successful AV implementation? - How do these drivers influence success?	- Which city type is best suited to AV deployment? - How should a city strategically align itself? Which scenario is best suited to which city type?	- How does fleet size affect the profit of AMoD fleet operators? - At which price level can the AMoD service be offered based on a per-kilometer view?
Research gap	- Current findings are partially inconsistent and contradictory - Missing comprehensive study on whether AVs can solve today's traffic burden and which factors influence AV success	- Current studies are spatially limited to specific cities - Missing study on the impact of AVs across numerous cities - Few studies provide a comprehensive strategic plan on how cities should orientate themselves with regard to their mobility concept for the future	- Only a few publications address the financial implications of AMoD systems holistically from a fleet operator perspective - Existing studies often use the same data sets, models, and cities – simulation-based approach for European cities is missing
Methodological approach	Traffic simulation		
	Literature review on conducted traffic simulations	Macroscopic traffic simulation	Microscopic traffic simulation
Data/Tool	236 peer-reviewed journal papers about how AVs impact cities based on traffic simulations	Continuous traffic simulation – data from 40 global cities	PTV MaaS Modeller – data from Gesamtverkehrsmodell Kanton Zürich
Contribution	- Evaluation of success factors for AV implementation - Contributes to the literature analyzing the impact of AVs on traffic and cities (Brown et al., 2014; Bissel et al., 2018; Simoni et al., 2019)	- First attempt to explore impacts of AVs on a large scale across different megacities - Identify different underlying urban structures that can help explain the potential for successful AV deployment	- Paper extends Boesch et al. (2018)'s cost analysis of AVs - Provides a starting point for exploring the financial implications of a realistic AMoD deployment in a representative European hub
	Recommendations for policymakers		Recommendations for fleet operator
	Recommendations on how to avoid negative consequences	Contributes to the literature by providing a strategic long-term plan for policymakers on how to prepare their city for the future (Thomopoulos & Givoni, 2015; Faisal et al., 2019).	Recommendations for fleet operators including measures for saving costs and for increasing operational efficiency
Status of article	Submitted to Transport Review	Submitted to Journal of Transportation Part A: Policy and Practice	Submitted to Research in Transportation Business & Management

Conclusion

This dissertation advances understanding of the impacts of AVs on today's cities and provides guidance on make AVs successful. The four articles establish links between existing AV simulations and its benefits for cities. Taken together, the four articles offer new insights by conducting various traffic simulations.

Political and managerial implications

Overall, the four articles highlight the importance of preparing for the future today. To do this, this dissertation provides different future scenarios on what the future might look like and how it might be influenced. Furthermore, the articles serve as a guideline on how different stakeholders (e.g., policymakers and fleet operators) can prepare today for tomorrow.

Article 1 first demonstrates that today's traffic is reaching its limits and negatively impacts cities and the environment. It emphasizes that policymakers need to understand how new emerging technologies (e.g., the implementation of AVs) can impact cities positively and negatively. Further, the listed recommendations show what can be done today to reduce the number of vehicle miles travelled, mobility costs, environmental pollution, land use, and traffic collisions to make AVs a success.

Based on the results of the traffic simulation in **Article 2**, recommendations are made on how politicians should align their long-term, AV-based urban strategies. Each city in the world can categorize itself along the developed clusters. According to these categories, politicians can decide whether to design their city for the future of AVs. The key findings highlight that AVs do not benefit every city in the same way. There are cities where alternative scenarios achieve a higher impact based on the six defined KPIs. Further, the results indicate that different strategies are needed to implement AVs in a city's overall mobility concept. Importantly, policymakers need to take responsibility for how such city strategies should best be aligned with the future.

From a managerial perspective, **Article 3** provides an ideal starting point for exploring the financial implications of a realistic shared autonomous vehicle fleet deployment in a representative European hub. Zurich, due to its size, infrastructure, and economy, represents a typical major urban area in central Europe. The obtained results can be transferred into implications and recommendations for other urban hubs of comparable size and role. Furthermore, this paper considers the most updated information, values, and cost developments.

Theoretical implications

The findings of this dissertation contribute to the research streams on AVs and urban mobility.

By comprehensively reviewing over 200 papers, **Article 1** identifies and consolidates the five main literature streams: traffic volume (i.e., Clements & Kockelman, 2017), mobility costs (e.g., Bansal & Kockelman, 2017; Boesch et al., 2018), safety (e.g., Chan, 2017; MacKenzie et al., 2014), environmental pollution (e.g., Brown et al., 2014; Wadud et al., 2016), land use (Duarte & Ratti, 2018; Yi et al., 2018). The article contributes to a growing body of literature on the impact of AVs on traffic and cities (Brown et al., 2014; Bissel et al., 2018; Simoni et al., 2019).

Policymakers on a national and regional level are urged to revise and adjust their transport strategies to avoid detrimental effects. However, most officials are not prepared to respond appropriately to the existing challenges (Thomopoulos & Givoni, 2015; Faisal et al., 2019). **Article 2** contributes to the literature by providing a strategic long-term plan for policymakers on how best to prepare their city for the future. The research is a first attempt to explore the impacts on a large scale across different megacities. Since most studies are spatially limited to specific cities (Fagnant & Kockelman, 2014; Farhan & Chen, 2018), and focus only on a few parameters (Zhao & Kockelman, 2018; Loeb & Kockelman, 2019), this article fills this research gap by applying a new traffic simulation approach.

Article 3 provides deeper insights into operator profitability due to fleet size and extends the existing literature (Boesch et al., 2016). The study is based on a procedure from the literature and supplements this with a microscopic traffic simulation (Noekel & Schaefer, 2018; Barceló et al. 2018). This results in a new approach to determining which parameters influence the costs of an AV fleet from the fleet operator perspective.

Article 1

Can Autonomous Vehicles Solve Today's Traffic Burden? – A Systematic Literature Review

Maximilian A. Richter

Abstract

The modern heavy car use includes negative consequences, whereby cities reach their limits in terms of pollution, congestion and land use. Autonomous vehicles (AVs) have the potential to relieve today's burden, although the effect of their implementation on roads and cities remains unclear. In a holistic approach, it is poorly understood which factors determine the influence. Simulation plays an important role in determining the effects of AVs. Based on 236 papers – filtered in a systematic literature research – in this paper it is estimated which factors influence the success of AVs. The main focus is to discuss the extent to which the corresponding parameters influence the success of AVs to make recommendations to boost the advantages. To explore AVs' success, first the author discusses five impact areas of today's traffic burden. Second, the author analyses how AV introduction affects roads and cities, highlighting the drivers for the specific impact area. Third, the author draws recommendations for action for policy-makers to initiate the emergence of AVs, while further discussion is presented from the perspective of researchers and policy-makers.

Keywords

autonomous vehicles, urban design, policy-maker, traffic burden, traffic simulation

Article 2

Assessing the Impact of Automated Vehicles on Cities with Differing Urban Structure

Maximilian A. Richter

Markus Hagenmaier

Oliver Bandte

Abstract

The impact that autonomous vehicles (AVs) will have on urban traffic in different cities around the world will largely depend on both the policies and strategic direction of the city and on the unique traits of a particular city such size, population or topography. This article presents a simulation-based comparison between different cities and autonomous vehicle adoption scenarios to understand what aspects of cities lead to positive AV implementation outcomes, and what aspects lead to negative outcomes. The analysis represents a first attempt to explore the impact of AVs at a large scale across different cities around the world. By simulating different scenarios - along six key performance indicators (KPIs) - on how AVs influence today's cities, the goal is to explore which cities benefit the most from AVs. For the analysis, city archetypes are formed by clustering different cities into categories and selecting a statistical city for each archetype. These archetypes are comprehensive in that they account for most, if not all, world cities. Using these city archetypes, a simulation is carried out for the different scenarios, taking into account the KPIs. The main finding is that cities with differing urban structure see different benefits and drawbacks from the introduction of AVs. While results vary for the different city structures considered, AV-shuttles have positive consequences for all city types. Based on these findings, we provide long-term political guidance on appropriate policy decisions relating to AV introduction in different city types.

Keywords

shared autonomous vehicles, traffic simulation, continuous space modelling, urban mobility

Article 3

Exploring the Financial Implications of Operating a Shared-Ride Autonomous Vehicle Fleet in Zurich

Maximilian A. Richter

Christoph Baur

Raphael Stern

Abstract

Implementing autonomous vehicles (AVs) has many advantages. The main advantages are achieved when AVs are offered as on demand services by a fleet operator. However, autonomous mobility on demand (AMoD) will be distributed nationwide only if fleet operation is economically profitable for the operator. This paper proposes a microscopic approach to modelling two implementation scenarios of an AMoD fleet, differing in fleet size of AVs. The city of Zurich is used as a case study, with the results and findings being generalizable to other similar European and North American cities. The data are based on the traffic model of the canton of Zurich (*Gesamtverkehrsmodell des Kantons Zürich* (GVM-ZH)). A macroscopic approach using the PTV MaaS Modeller tool is used for the simulation. To determine financial profitability, demand is based on the simulation results and combined with analyzing the costs of an AV per kilometer. The results demonstrate that depending on the scenario journeys can be offered profitably to customers for CHF 0.44 or CHF 0.52 per kilometer. While larger fleets allow for lower price levels and increased profits in the long term, smaller fleets exhibit elevated efficiency levels and profit opportunities per day. The paper concludes with recommendations for how fleet operators can prepare themselves to maximize profit in the autonomous future.

Keywords

autonomous vehicles, autonomous mobility on demand, fleet provider, microscopic traffic simulation

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Article 1

Can Autonomous Vehicles Solve Today's Traffic Burden? – A Systematic Literature Review

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Abstract

The modern heavy car use includes negative consequences, whereby cities reach their limits in terms of pollution, congestion and land use. Autonomous vehicles (AVs) have the potential to relieve today's burden, although the effect of their implementation on roads and cities remains unclear. In a holistic approach, it is poorly understood which factors determine the influence. Simulation plays an important role in determining the effects of AVs. Based on 236 papers – filtered in a systematic literature research – in this paper it is estimated which factors influence the success of AVs. The main focus is to discuss the extent to which the corresponding parameters influence the success of AVs to make recommendations to boost the advantages. To explore AVs' success, first the author discusses five impact areas of today's traffic burden. Second, the author analyses how AV introduction affects roads and cities, highlighting the drivers for the specific impact area. Third, the author draws recommendations for action for policy-makers to initiate the emergence of AVs, while further discussion is presented from the perspective of researchers and policy-makers.

Keywords

autonomous vehicles; urban design; policymaker; traffic burden, traffic simulation

1 Introduction

Since the beginning of urbanization, mobility has been a key driver of growth and progress (Alam et al., 2011; Igliński & Babiak, 2017). Cars have strongly changed and shaped countries and their cities. Since their mass-market adoption about 50 years ago, urban space has been filled with infrastructure designed for cars, such as roads and parking spaces. This invasion has been pushed by policy-makers, as for years having more roads and infrastructure was associated with increased prosperity (UN Habitat, 2013). Nowadays, it is known that if you build a road, cars will come to use it. This is the rule of the road, which is derived from Braess's paradox (Steinberg & Zangwill, 1983).

Hamstrung traffic has wider negative impacts such as an elevated output of pollution, a high number of fatalities, a lack of public space and social injustice due to high mobility prices. All combined, today's traffic leads to a reduced quality of life (Dratva et al., 2010). Nowadays, policy-makers are facing a change in mobility and seeking new solutions to counteract individual motorized traffic (Cathkart-Keays, 2015; Nieuwenhuijsen & Khreis, 2016). In this context, autonomous vehicles (AVs) are regarded as one such technology that could signal a major change in mobility and they are also believed to be a remedy for today's traffic burden (Milakis et al., 2017). However, it is questionable what impact AVs will have and whether they can indeed solve today's traffic burden.

Since AVs are not yet commercially available, the effects resulting from this new technology cannot be fully estimated at present (Zmud & Sener, 2017). The literature showcases that research is conducted on the impact of AVs on traffic and cities (Brown et al., 2014; Bissel et al., 2018). However, results from current studies show that the findings are partially inconsistent and contradictory. Furthermore, to the author's knowledge no study has yet been conducted to comprehensively investigate whether AVs can solve today's traffic burden and what factors influence AVs' success.

Although AVs still have to overcome several technical challenges, many studies agree that their success will mainly be influenced by policy-makers, as they have a significant role to play in shaping the impact of AVs (Anderson et al., 2014; Clark et al., 2016; Enoch, 2015). It is even claimed that one of the leading risks of AVs is that if the implementation is mismanaged, they will reinforce the problems of car dependency, including its environmental, health-related and negative social consequences (Papa & Ferreira, 2018). Thus, favorable regulation is an essential prerequisite for AVs' successful introduction.

This study aims to identify whether AVs can contribute to solving the current traffic challenges according to the defined five impact areas. A further goal is to identify the drivers and their effects on the respective impact area to provide recommendations for action to make AVs as successful as possible. The paper serves to provide both researchers with an overview of the literature and policy-makers with an improved understanding of how AVs affect their cities.

The following research questions are formulated for this purpose:

- *Which impact areas can be identified that are affected by traffic today?*
- *What impact will the implementation of AVs have on roads and cities? What influences the different impact areas?*
- *How can policy-makers prepare cities for a successful implementation of AVs in their long-term urban and mobility planning?*

To answer these questions, chapter 2 presents the extent of today's burden that results from traffic, whereby the effects are summarized in five impact areas. Chapter 3 describes the method of the systematic literature review. Chapter 4 addresses the influence of AVs on traffic and the factors influencing this impact are analyzed. In chapter 5, recommendations for action for policy-makers are derived, contributing to a successful implementation of AVs.

2 Today's traffic burden

Vehicles are one of the major innovations of the past century and they have defined many aspects of modern society, including today's cities and civic interactions (Gilroy, 2001). Many experts agree that a sophisticated street network and comprehensive infrastructure are among the key drivers bringing economic growth and prosperity into cities (Morrish & Brown, 1995; Mboup, 2013; UN Habitat, 2013; Turok & McGranahan, 2013). However, a variety of new problems have emerged, including the following:

Traffic flow: Traffic and its resulting congestion is the bane of city life, and one of the most lamented transport problems (Leonard, 2018). According to the consulting firm Inrix (2019), people in major cities around the world spend an increasing amount of time every year stuck in traffic. For example, in London, each driver spending an average of 227 hours in congestion per year results in major financial losses of \$ 2,130¹ per person due to lost productivity and increasing mobility expenses, which costs the

¹ Converted from local currency (£1 = US-\$ 1.27) as of 22.02.2020.

governments billions (Inrix, 2019). The situation is becoming increasingly intense in most countries because congestion is deteriorating. While only 63 cities in a TomTom ranking were able to slightly reduce congestion, levels have increased for 239 cities, underlining the negative development (TomTom, 2020).

Mobility costs: While mobility issues in developing countries illustrate a comprehensible problem due to low per capita income, even well-developed parts of the world like the US and Europe face mobility cost-related issues (Wegener, 2009; Buettner, 2016). Tensioning housing markets with ascending real estate prices in large cities push lower-income households to remote suburban areas and with increasing distance to urban hubs, whereby such households are obliged to spend more money on mobility (Buettner et al, 2013). Car-dependent people are forced into car ownership that transcends their budget and limits their disposable household income, thus further reinforcing the vicious circle (Mattioli, 2017). Even more severely, those who cannot afford or access a certain level of mobility are often subject to mobility poverty, which prevents them from “participating in the economic, political and social life of the community” and leads to social exclusion (Kenyon et al., 2003, p. 210).

Safety: Ranking among the global top ten causes of death – and the leading cause of death for young adults aged 5-29 – road injuries have become a substantial risk for the population (WHO, 2018; WHO, 2020). While every year approximately 1.35 million people are killed as a result of road traffic collisions, up to 50 million people suffer non-fatal injuries, many of which leave the person disabled. One striking aspect of these figures is that more than half of the deaths can be attributed to “vulnerable road users” such as pedestrians, cyclists and, motorcyclists (WHO, 2020). Unless there is sufficient action taken by policy-makers, road traffic fatalities are predicted to become the fifth leading cause of death by 2030 (WHO, 2013). Each year, nearly 400,000 people under 25 die on world’s roads caused by vehicles (ASIRT, 2019).

Environmental pollution: During times of emerging climate debates, transportation accounts for nearly one-quarter of all greenhouse gases (Stead et al., 2017). While transportation CO₂ has steadily increased by about 1.6% over recent years, road vehicles such as cars and buses account for up to three-quarters of these emissions (IEA, 2019). According to the World Health Organization (WHO), over 90% of the world’s population live in locations where air pollution fails to meet the agency’s guidelines. Even more serious is the fact that the WHO now calls urban pollution levels a “public health emergency” (WHO, 2019). Studies in North America have found that long-term

exposure to air pollution increases the risk of diabetes, obesity, mental health problems, and emphysema, while in Europe poor air quality causes about 400,000 premature adult deaths a year (Clementi et al., 2019; Wang et al., 2019).

Land use: To achieve productivity in cities, people and jobs must be brought together, which comes at the cost of high urban density (Venables, 2015). In Germany, newly-built apartments over the past three years have covered only 80% of the demand for housing, according to The German Economic Institute (2019), making urban space highly valuable. Poor land use policies place further limitations on available space, ultimately forcing people out of certain areas, which results in lost potential and social exclusion (Macias, 2015; Turok, 1999). Especially in historically-planned cities such as Barcelona, Hong Kong, and Manhattan, more than one-third of all land is devoted to roads or parking spaces (UN Habitat, 2013). New York has more than three million parking spaces, equivalent to over half a parking space per household (Shoup, 2018). In the densest cities in India such as Mumbai and Delhi, a parking bay takes up more space than a low-income family of four (Gauthier, 2012).

3 Methodological approach

To achieve the research aim and objectives, this paper approaches a systematic literature review, which follows a four-step process.

Table 1
Four-step process for the systematic literature review

Process Step	Methodology	Result
1. Framing	Identification of relevant outlets, keywords, selection criteria, scope & boundaries	Document with search approach outline and key criteria
2. Search & Selection	Comprehensive literature search and exclusion of unsuitable sources	XLS sheet with relevant literature (n=236)
3. Analysis	Full-text review, extraction of relevant information & allocation to five main AV impact areas	XLS sheet with analyzed and classified literature (n=86)
4. Synthesis & Evaluation	Development of structures, deduction of key information, quantitative appraisal	Document with qualitative and quantitative results

- 1. Framing:** In order to enable a comprehensive and structured search, pre-selected keywords and search strings were determined (Tranfield et al., 2003). The search terms were derived from the results of the prior analysis (Chapter 2) and comprised the five main AV impact areas of traffic, mobility costs, safety, environmental pollution, and land use. To narrow the scope to AV effects, the

search string was complemented with a selection of synonyms to capture potential euphemisms (Table 2).

Table 2
Keywords and search string

AV	+	Effect	+	Area
Autonomous Car(s); Autonomous Vehicle(s); Autonomous Driving; Driverless Car(s); Robocar(s); Self-Driving Car(s); Self-Driving Vehicle(s); Vehicle Automation		Impact(s); Effect(s); Ramification(s); Outcome(s); Implication(s)		Traffic; Congestion; Flow; Capacity; Safety; Crash(es) Collision(s); Risk; Cost(s); Value of Time; Ownership; Replacement; Sharing; Environment; Pollution; Fuel; Energy; Emission(s); Location Choice; Land Use; Urban

2. Search and selection: To allow for an outlet-independent assessment, Web of Science² was utilized as the primary database. Although AVs can be considered a recent phenomenon that has mostly covered throughout the past decade, no particular limitation was defined regarding the date of publication to allow for early explorations. Publications were included up to December 2019, when the search was conducted. Carrying out the search process, the search range was restricted to the title, abstract and keywords of the papers and was limited to the English language. An initial result of 2,425 papers was further confined based on the relevance for this research. In uncertain cases, the abstract was considered in an ancillary manner and extraneous research was excluded. In addition to the primary research, Google Scholar was used such as a backward approach to collect further reports by reviewing the citations in previously-identified literature (Webster & Watson, 2002). Institutional or governmental reports were not included. This process led to a total of 236 relevant papers that were captured in an Excel sheet, which served as the starting point for the further process. Key information such as the author, year of release and outlet of the relevant literature was annotated to enable an overview of the literature.
3. Analysis: The full-text review as part of the analysis process helped to focus on and select the most relevant publications. All entered papers were read and examined concerning their extent of value addition for the underlying research. A focus was placed on main outlets in the area of transportation research with quantitative approaches such as simulations, experiments, and surveys assessing AVs and their impact based on key performance indicators (KPIs). The derived

² www.webofknowledge.com

KPIs were then assigned to the five main AV impact areas, resulting in a final dataset of 86 papers (Table 3).

Table 3
Overview of impact areas

Impact Areas	Traffic	Safety	Costs	Environment	Land Use
<i># of Papers</i>	<i>47</i>	<i>14</i>	<i>11</i>	<i>34</i>	<i>18</i>
KPIs ³	Vehicle Miles Traveled	Collisions / Crashes	Purchasing Premium	Energy / Fuel Consumption	Removable Parking Space
		Fatalities	Operational Costs	Emissions	People Moving

4. Synthesis and evaluation: The final step of the process comprised the qualitative and quantitative analysis of the literature. If procurable, averages and outliers of the KPIs were calculated to synthesize the expectable impact. Subsequently, a brief qualitative analysis was performed to extract the rationales and justify the quantitative assertions.

4 Impact of AV implementation on cities along five defined impact areas

4.1 Traffic flow

Vehicle miles traveled (VMT) is an integral measure in transportation planning and it quantifies “the amount of travel for all vehicles in a geographic region over a given period of time” (Williams et al., 2016, p. 6). This KPI is used to determine the traffic flow, since it is widely used as a representative measure for traffic impact evaluations and has shown to significantly affect traffic congestion (Kim et al, 2016; Clements & Kockelman, 2017).

The considered studies show that the implementation of AVs has an effect on VMT of between -35% and +341%, whereby the mean value is an increase in VMT by 27.3%. The outliers for a reduction in the VMT (<0%) result from the strong capacity gain due to AVs (Patella et al., 2019), high road tolls for AVs (Simoni et al., 2019) or the exclusive offer of AVs as a shared vehicle (Davidson & Spinoulas, 2016). Outliers for an increase of >50% result from scenarios in which cars no longer need to park and instead drive permanently to ideally serve traffic demand (Zhang et al., 2015; Bischoff et al., 2018), or scenarios that are simulated under very low costs due to AVs (Harb et al., 2018). Overall, AV technologies lead to an increase in average trip distance. Auld

³ Due to a thematic overlap, some papers are assigned to multiple impact areas.

et al. (2019) predict an increase from 11.8 miles to 17.4 miles (increase by 47%), whereas Kroeger et al. (2019) predict an increase of 8.6%. There are three primary factors identified that influence the VMT, namely empty rides, the cost of travel and new user groups.

Empty rides

The use of AVs leads to empty trips, which generate additional VMT (Alam & Habib, 2018). It was identified that empty miles are differentiated by two types of use, namely those AVs that are shared between customers (pick-up drive) and non-shared AVs.

Shared AVs: If several users share an AV one at a time, the repositioning of the vehicle to serve the trip requests creates an empty journey between the trips (Chen et al., 2016; Zhang et al., 2018). The VMT increase due to empty runs is quite significant. Auld et al. (2019) predict an increase of 15% in VMT due to empty miles by reallocation, whereas Simoni et al. (2019) forecast an increase of 6% in total VMT and Chen et al. (2016) predict an increase by 8%.

Private AVs: In case AVs are used as private vehicles, empty miles mainly arise from parking and recharging between trips. The typical commuter route ends in the city center, where parking spaces are rare and expensive. For AVs, there are therefore three options after dropping off the user: find the nearest parking lot (Bischoff et al., 2018), finding the cheapest parking lot, which is often out of town (Harper et al., 2018), or cruising around until the driver needs the car again (Shoup, 2006). The first two scenarios usually have marginal effects (2-4%) (Bischoff et al., 2018), whereas cruising has drastic effects and can double VMT even at low penetration rates (Bischoff et al., 2018). Vehicles could also be used for purposes other than passenger travel, such as picking up groceries. Harb et al. (2018) stated this effect with an increase of 34% in VMT.

Cost of travel

Operating costs: Vehicle automation leads to a reduction in operating costs per mile (chapter 4.2), which increases the attractiveness of AVs. Since the purchase barriers are initially high, this effect is mainly reinforced when AVs are offered as an on-demand service. When AVs are operated at low prices, people prefer them over public transport or bikes as the fare rate determines choice (Simoni et al., 2019; Liu et al., 2017). Bischoff and Maciejweski (2016) predict a 13% increase due to shared AVs.

Value of travel time (VoTT): “VoTT is defined as an individual’s willingness to pay to avoid another hour of travel” (Zhao & Kockelman, 2018, p.1). Hence, the lower

the VoTT value, the higher the usage of a specific traffic mode. Although qualitative studies indicate that VoTT for AVs will not significantly change (e.g. due to skepticism, boredom, etc.) (Cyganski et al., 2015), most quantitative studies show that journey distances will increase due to freed-up time for other activities. Wadud et al. (2016) predict an increase due to the reduced costs of drivers' time from 4% in VMT for low-level automation to around a 60% increase for level 4 automation - vehicles are capable of steering, accelerating, and braking on their own - for light duty travel alone.

New user groups

AVs have the potential to increase the mobility of the currently-unserved population, such as people without a driver license, travel-restrictive medical conditions, or seniors (Harper et al., 2016). These three groups lead to a VMT increase of 14% for regular usage patterns (extrapolated from other user groups), according to Harper et al. (2016). In addition, there are other groups that were not included in the studies (e.g. people in wheelchairs or young people and children). Wadud et al. (2016) predict that the use by pensioners alone will cause an increase of 2-10% in overall VMT.

4.2 Mobility costs

It was established that there are two contrary effects on mobility costs when AVs are applied: the purchase price of vehicles with autonomous equipment will rise, while the cost of use per kilometer will fall. AVs could become up to 16,000 \$ more expensive due to new technologies, while in an extreme scenario the cost per kilometer could drop by more than 80% if they are used as a shared vehicle.

Purchase price

All considered papers that covered the purchasing price of AVs agreed that once they are released in the market, buyers will have to pay a certain premium compared with a conventional vehicle (Abe, 2019; Bansal & Kockelman, 2017; Boesch et al., 2018; Chen et al., 2016; Fagnant & Kockelman, 2015; Harper et al., 2016; Jones & Leibowicz, 2019; Wadud, 2017). It would be unreliable to make a statement about how much an AV costs, because the purchase prices presented in the considered studies are partly simplified, do not differentiate between user groups or made no distinction between luxury and small cars. Nevertheless, various components influence the purchase price and indicate how the cost of AVs may develop. While Bansal and Kockelman (2017) and Harper et al. (2016) explain the price increase with a variety of automation features, Boesch et al. (2018) also consider the battery as the main cost driver. Technologies that enable autonomous driving – such as blind spot monitoring, lane departure warning and

forward collision warning – cost about \$600 (Harper et al., 2016). LIDAR (Laser detection and ranging) technologies can amount to \$8,000 extra (Wadud, 2017). There are also costs for the software, which can make up \$10,000 extra (Wadud, 2017). Table 4 shows how much more expensive AVs could become, whereby depending on the valuation additional costs of \$7,500 to \$16,600 can be expected. Due to learning effects and technical progress the price will drastically decrease at about 9% in a linear manner according to Jones et al. (2019), and 5-10% according to Wadud et al. (2017). Bansal and Kockelman (2017) predict a 5% learning rate. In the long term, with high market penetration and more than ten years in the market, the technology of AV will be only \$1,000 to \$3,000 according to Fagnant and Kockelman (2015) and Jones and Leibowicz (2019).

Table 4
Cost of AV technology

Source	Time of prediction	Cost of premium
Chen et al. (2016)	2025	\$10,000
	5-10 years in the market	\$3,500 - \$5,000
Bansal & Kockelman (2016)	2020	\$31,000
	2025	\$24,000
	2030	\$18,500
Jones & Leibowicz (2019)	2020	\$7,500 - \$10,000
	2030	\$1,000
Wadud (2017)	2020 when first in market	\$13,700 - \$16,600
	2025	\$9,800
Fagnant & Kockelman (2015)	10% Market Share	\$10,000
	50% Market Share	\$5,000

Costs of use

Spieser et al. (2014) show that the costs of use for consumers can be divided into explicit costs of services and hidden costs. Explicit costs (e.g. insurance premium, fuel, etc.) can be quantified directly, whereas hidden costs are rather abstract. Furthermore, studies show that sharing also has a strong influence on the costs of use (Boesch et al., 2018; Abe, 2019).

Explicit cost of service

The explicit cost of service is defined as the sum of all explicit costs associated with accessing mobility. According to the considered studies, five costs were identified, all of which are predicted to be lower due to AVs compared with conventional vehicles.

Insurance costs: Moderate estimates amount to 50% savings (Boesch et al., 2018), while optimistic estimates state a 60-80% savings potential (MacKenzie et al., 2014). The reductions result from the fact that AVs are expected to reduce collisions (MacKenzie et al., 2014). In addition, the cost advantage of electric cars – which are up to 35% cheaper – must be taken into account (Boesch et al., 2018). However, these savings can only be achieved via a "volume effect", i.e. when other road users are also automated. Therefore, a 20% reduction for fully-automated vehicles appears reasonable at early stages, according to Wadud (2017).

Fuel efficiency: The automation of a vehicle brings many advantages for fuel efficiency. Due to eco-driving and eco-routing as well as improved braking behavior, platooning and traffic avoidance, savings of up to 20% can be achieved in the long term (MacKenzie et al., 2014). Platooning alone can reduce fuel expenses by 2% (Brown et al., 2018). Added to this, the "de-emphasises performance" (AVs are no longer a status symbol and have significantly less horsepower) can lead to another 5-23% saving (Wadud, 2017).

Maintenance: The maintenance costs of AVs are a rather unclear effect. Electric motors are much less susceptible to damage, which can reduce maintenance and repair costs by up to 35% (Boesch et al., 2018). However, costs can also increase by up to 28% due to the earlier replacement of motors, maintenance costs due to automation, etc. (Boesch et al., 2018).

Parking: The sharing function prevents cars from having to be parked during the day. Those who do not want to share their car can move their parking spaces to cheaper areas, as the cars can drive on their own. Accordingly, savings averaging \$250 per AV per year can be expected (Fagnant & Kockelman, 2015).

Value of travel time (VoTT): "One of the biggest costs of driving is the waste of travel time that does not generally enter the (...) analysis" (Wadud, 2017, p 7). VoTT can account for up to 40-60% of the explicit costs of driving (Wadud, 2017). Estimates regarding the extent to which VoTT can be reduced by AVs range from -80% to -5%. Wadud (2017) uses upper and lower bounds from a -60% to -25% VoTT reduction. The VoTT is currently specified at about \$0.96/km (Liu et al., 2017) or \$17.67 per hour (Liu et al., 2017). Using AVs, VoTTs of \$0.22/km or \$8.84/h can be achieved, which means 50% to 70% savings (Liu et al., 2017; Spieser et al., 2014).

Table 5 concludes the saving potential identified in the studies. A distinction was made between short- (within 5 years of AV introduction) and long-term savings potential (more than 20 years after AV introduction).

Table 5
Change in explicit costs due to AVS

Explicit cost of service	Short-term savings	Long-term savings
Insurance	-20%	-80%
Fuel efficiency	-10%	> -20%
Maintenance	unclear	unclear
Parking	\$250 / AV and year	> -50%
VoTT	< -50%	> -50%

Sharing of AVs

Using the AV as a shared car leads to a reduction in costs as such costs can be shared among individual users. Taxis and shared taxis have the strongest benefit due to the driver salary saving (Wadud, 2017). Some papers have broken this down to the cost-measured price per mile, which is shown in Table 6.

Table 6
Cost per mile comparison

Source	Method	Cost per mile	Effect	Comment
MacKenzie et al. (2014)	Quantitative Study	\$1.16	-	Conventional car travel
		\$0.65	-40%	AV costs in general
Chen et al. (2016)	Quantitative Study	\$0.42	-	SAEV
		\$0.43	-	SAEV fast charge
		\$0.49	-	SAEV long range
		\$0.48	-	SAEV fast charge and long range
		\$0.85 ^{4,5}	-	Human-driven vehicle in the US
Spieser et al. (2014)	Quantitative Study	\$0.44 ^{5,6}	-48%	Shared self-driven car
		\$0.59 ^{5,6}	-31%	Shared dual-mode car
		\$0.51 ^{5,6}	-40%	Personal self-driving car
		\$1.21 ⁵	-	Individual taxi: non-autonomous
Boesch et al. (2018)	Quantitative Study	\$0.20 ⁵	-83%	Individual taxi: autonomous
		\$0.71 ⁵	-	Pooled taxi: non-autonomous
		\$0.13 ⁵	-81%	Pooled taxi: autonomous
		\$0.30 ⁵	-	Private car: non-autonomous
		\$0.32 ⁵	+4%	Private car: autonomous

⁴ Converted from km to miles (factor of 0.62).

⁵ Converted from CHF to USD (factor of 1.02) as of 22.02.2020.

4.3 *Safety*

Fifteen out of fifteen analyzed papers came to the conclusion that AVs will certainly reduce collisions, with the two remaining publications also stating the overall positive effects as well as including negative scenarios. To elucidate AV effects on traffic safety, researchers make use of three arguments: the eradication of human error, crash avoidance technologies within the car and safety-improving features of the environment (Table 5). Clements and Kockelman (2017), Fagnant and Kockelman (2015), Chan (2017), MacKenzie et al. (2014), Morando et al. (2018) and other researchers follow the line of reasoning that since 94% of collisions are caused by human error (NHTSA, 2015), a 100% AV penetration rate will reduce crashes by about that amount. However, this notion is subject to criticism as it is based on the assumptions that new technology is thoroughly faultless and a full market penetration of fully autonomous cars can be achieved, both of which seem highly unlikely in the foreseeable future (Chan, 2017). The second approach implies the inclusion of certain technology in AVs that solely target the prevention of crashes (Eby et al., 2016). While a variety of sensors and technologies potentially contribute to improving the safety of AVs, merely three main technologies – forward collision warning (FCW), lane departure warning (LDP) and blind spot monitoring (BSM) – already have the potential to prevent up to 24% of crashes, according to Harper et al. (2016). Moreover, electronic stability control (ESC) – which counteracts slipping through brake intervention – could avert up to 14% of traffic deaths and 6% of collisions that leave passengers injured (Milakis et al., 2017). Finally, AVs are not only capable of communicating with each other but also the environment and infrastructure. Dresner and Stone (2008) state that automobile traffic with autonomous driver agents and an intersection control mechanism will reduce collisions in intersections by over 80%. Moreover, variable speed limits that homogenize traffic flows depending on the traffic situation could reduce the number of collisions by up to 11% (Khondaker & Kattan, 2015).

Table 7
Safety impacts by AVs

Improved safety through ...	Author	Scenario	Impact on crashes
Eradication of Human Error	Clements & Kockelman (2017); Fagnant & Kockelman (2015); Chan (2017); MacKenzie et al. (2014); Morando et al. (2018)	100% AVs penetration rate, no human drivers	- 90% to -94%
In-Car Crash Avoidance Technology	Harper et al. (2016)	100% penetration rate of FCW, LDP & BSM	-24%
	Milakis et al. (2017)	75% penetration rate of ESC (injury collisions only)	-6%
Communication w/ Smart Infrastructure	Dresner & Stone (2008)	Communication with intersections	-36% ⁶
	Khondaker & Kattan (2015)	Variable speed limit	-11%

While the overall impact on safety is positive in all papers, negative effects are likely to be expected in the transition phase (Chan, 2017). In a short-term scenario with moderate AV share, Davidson and Spinoulas (2016) highlight that crash avoidance technologies might not be able to compensate increased VMT from AV and non-AV vehicles, which leads to an overall increase in the number of crashes. Khondaker and Kattan (2015) emphasize the high sensitivity of safety measures to the relative speed and positions of the vehicles in their simulation. With a 50% AV penetration rate, uncertainty regarding traffic and certain optimization configurations also prove to slightly increase the collision risk. As a result, a correlation between AV penetration and the safety impact can be drawn that corroborates notion that with more AVs on the road, the stronger the safety impact (Table 8). Thus, in order to realize the full safety benefits, high AV penetration rates are required to avoid interference factors (Morando et al. 2018).

⁶ 80% fewer crashes on intersections, which account for up to 45% of all collisions.

Table 8

Positive correlation between AV penetration rate and the impact on collisions

Autor	Method	Scenario/ Penetration Rate	Impact on Collisions
Fagnant & Kockelman (2015)	Quantitative Study	10% AV Penetration	-50% (per AV) -4% (total network)
		50% AV Penetration	-34% (total network)
		90% AV Penetration	-90% (per AV) -77% (total network)
Davidson & Spinoulas (2016)	Simulation	12% AV Penetration	+16% (total network)
		42% AV Penetration	-14% (total network)
		62% AV Penetration	-33% (total network)
		100% AV Penetration	-67% (total network)
Morando et al. (2018)	Simulation	50% AV Penetration	-20% (at simulated intersection)
		100% AV Penetration	-65% (at simulated intersection)

While researchers mostly conclude positive safety repercussions, controversies that are not considered in most studies can also counteract the effect of reducing collisions. New emerging risks may arise, such as defective systems. In addition, it is presumable that more risks will be taken while driving, which will result in an offsetting behavior (Milakis et al., 2017). Furthermore, platooning reduces the headways between cars and thus the time to collision. Although this effect might increase the collision rate, real-time communication and more homogeneous speeds would reduce the number of serious collisions (Carbaugh et al., 1998).

4.4 Environmental pollution

The absolute significance of the analysis is low as certain studies focus on individual environment components (e.g. CO only, fuel, etc.) or specific effects such as the extent to which autonomous lane change improves NOX emissions (Ioannou & Stefanovic, 2005). Others attempt to classify environmental effects holistically (MacKenzie et al., 2014; Brown et al., 2014; Wadud et al., 2016). Nevertheless, all values considered, there is a reduction of around 10% in the emission of harmful substances. Therefore, AVs have a positive effect on the environment.

In order to better understand the influence of AVs on environmental factors, the effects are broken down in Table 9.

Table 9

Change in pollution based on specific effects

Effect	Brief definition	MacKenzie	Brown	Wadud	Other
Congestion	Reduced Congestion	up to -4%	-5%	up to -4%	
Eco-driving	Increased fuel efficiency	up to -20%	-40%	up to -20%	-11.8%
Platooning	Multiple vehicles follow each other closely	-3% to -25%	-10%	-3% to -25%	Up to -89.8% total vehicular traffic emissions
De-emphasized Performance	Reduced acceleration times	-5% to -23%		-5% to -23%	
Vehicle configuration	Reduced vehicle weight	-5,5% to -23%	-50%	-5,5% to -23%	
	Increased vehicle weight	/	/	+11%	
Vehicle right-sizing	Matching seat capacity demand	-21% to -45%		-21% to -45%	
Speed	Higher travel speeds	+4% to +25%	+30%	+7% to +22%	
Mobility cost	Reduced travel costs for riding	+4% to +156%	/	+4% to +60%	
New user groups	Increased travel by underserved	+2% to +10%	+40%	+2% to +10%	
Travel behavior	Increased travel distance and frequency	/	+50%	/	
Car sharing	Autonomous taxis, reduced ownership	up to -20%	-12%	up to -20%	-50% for high sharing, high penetration
Engine	Alternative fuel technologies	/	-75%	/	
Parking search	Unoccupied search for cheapest parking spot	/	-4%	/	+2,1%
Worst/best case	/	-45% to +100%	-96% to +173%	-45% to +100%	

When considering the environmental impact of AVs, the life cycle view of the vehicles is neglected. These emissions were only considered to a minor extent in the observed studies. Patella et al. (2019, p.199) state that AVs are characterized by the highest “Greenhouse Gases (GHG) emissions related to construction, maintenance and end-of-life processes that resulted on average a 35% higher than the ones of ICEVs, a 22% higher than the ones of HEVs vehicles and a 5% higher than the ones of BEVs”. Brown et al. (2014) state that AVs will have significantly shorter life expectancies than conventional cars ("Parked 95% of the time") due to their high utilization. While the shorter life cycle has a negative impact on the environment (through production and

recycling), it enables a continuous renewal of the technologies used, which are expected to become more environmentally friendly over time.

4.5 Land use

Researchers emphasize that AVs will lead to a decrease in public areas needed for road transportation. However, it will take some time before parking spaces actually become eliminated and since many parking spaces are privately owned, much more moderate effects should be expected (Clements & Kockelman, 2017). Three effects of AVs on land use were identified:

Decrease in land use: All of the authors considered agree that the main factor that could be freed and repurposed is parking space. At present, 3-4 parking spaces are required for each vehicle in an urban context (Zhang et al., 2015). The proportion of roads in large cities is usually around 30%, and up to 36% (UN Habitat, 2013). Herby, curb parking can account for up to 5-8% of the city area and parking areas generally occupy up to 15% of the space within cities. It is estimated that in the future each AV will be able to eliminate between eleven (Fagnant & Kockelman, 2014) and twenty (Duarte & Ratti, 2018) parking spaces. Zhang et al. (2018) predict that a 50% AV penetration rate with 10 minutes allowed cruising time could eliminate about 90% of parking spaces in cities. Other effects that have a positive impact on the area are associated with the transport infrastructure (Duarte & Ratti, 2018). For example, in the long term, traffic lights could be removed (as cars can communicate with each other and the environment), or roads could be narrowed due to the lateral accuracy of AVs. However, these effects have not yet been quantified.

Increase in land use: The smooth operation of AVs requires new space, whereby car sharing needs the presence of adequate charging infrastructure and space allocated for stations, as well as on-street parking (Mounce & Nelson, 2019). Yi et al. (2018) highlight the number of charging stations needed to load AVs, which is accompanied by challenges such as securing the power grid. Moreover, AVs need to be maintained or parked in periods of low demand to avoid additional VMT. This requires additional infrastructure, which has also not yet been quantified (Yi et al., 2018).

Urban sprawl: This is another effect concerning the use of land. Duarate and Ratti (2018) state that AVs could prompt people to decide to move even further from cities. An effect that could lead to urban sprawl is the time saved by AVs, by allowing other tasks to be performed while driving and reducing prices for housing in suburbs (Clements & Kockelman, 2017). On the other hand, it can be assumed that if access to automated services is limited to certain areas, users will prefer to move to these areas

(Zmund & Sener, 2017). This is true for shared AVs if they only operate in a certain zone (Gelauff et al., 2019). Another effect that could lead to an influx into cities is the released parking space in the form of residential buildings and falling prices (Faisal et al., 2019). The exact impact that AVs will have is unclear, although a pro-urban sprawl tendency is evident. Clements et al. (2017) compare the effects and assume a slight outward expansion from 7.4% to a movement in urban areas from 11%. In general, this could mean that large cities will become larger and small cities smaller.

5 Discussion and implications

Without counter-measures, AVs will not be able to solve the traffic and congestion problem. Although new technologies will improve traffic flow, there are effects that increase the demand for road travel when vehicles operate as AVs. To control the extra VMT, policy-makers must initiate appropriate actions to reduce the increase:

- **Increase the attractiveness of public transportation:** Making public transport more attractive prevents people from switching to AVs (Gruel & Stanford, 2015). To achieve this, new last-mile services need to be offered (Kroeger et al., 2019) and AVs must be used to facilitate rather than replace access to public transport (Patella et al., 2019).
- **Introduce toll policies:** Toll policy may play a role in controlling the total VMT. Davidson and Spinoulas (2016) state that the best approach would be to implement road pricing. Kroeger et al. (2019) extend this even further and recommend intelligently-designed road pricing, which might help to avoid the negative consequences.
- **Prevent empty runs:** Although AVs have the potential to reduce the number of vehicles on the roads, empty rides in particular pose a major problem when AVs reposition themselves or travel between passengers. This could be counteracted by "unoccupied VMT" fees (Zhang, Guhathakurta & Khalil, 2018).

Mobility costs comprise two opposing trends, whereby it is predicted that the purchase price of vehicles will initially sharply rise, but the cost of use will fall. As a result, AVs in private use will not initially contribute to reduced mobility costs. Nevertheless, if AVs are offered as an on-demand service, costs can sharply decline and thus reduce the mobility costs of many people, as they no longer have to rely on expensive individual vehicles.

- **Support autonomous on-demand services:** It is much more affordable to access mobility in an autonomous mobility-on-demand system compared with traditional mobility models based on private vehicle ownership (Spieser et al., 2014).
- **Develop business models:** Cities can proactively participate in developing business models and can thereby control the prices for on-demand trips (Abe, 2019). This is particularly important in low-density areas where privately-operated SAV concepts are not profitable.

Safety will likely increase in the long term through AVs. Nevertheless, the transition phase during which AVs are slowly implemented is challenging, as road safety will continue to be influenced by non-AVs. From a global perspective, 90% of road deaths occur outside North America, the European Union, Japan and Australia (Chan, 2017). Especially outside of these regions, AV scenarios are extremely unrealistic in the short term (Chan, 2017). The global impact is therefore likely to be low compared with the total number of fatalities. Nevertheless, safety can be improved through certain measures:

- **Introduce AV-only zones:** “The full benefits of autonomy will not be realised until manual vehicles are removed from most roads” (Davidson & Spinoulas, 2016, p. 15). Ideal effects are only achieved when there are no manual vehicles that obstruct AVs. In this respect, AV-only zones (e.g. lanes on the motorway) could be introduced in places to achieve the full effects.
- **Vehicle-to-infrastructure communication:** Cities should create the necessary infrastructure as soon as possible to maximize the safety effects of AV. This includes intersection control as well as traffic signal timing (Dresner & Stone, 2008).
- **Foster the implementation of autonomous driving systems (ADS):** Security can also be increased if the technology of AVs is not yet fully developed. Equipping new vehicles and upgrading old vehicles with so-called ADS can reduce the number of collisions. If such systems become compulsory, the number of injuries and fatalities will be reduced.

AVs have the potential to reduce environmental pollution. However, taking into account the entire life cycle, this effect is significantly weakened. The impact on pollution is strongly related to other factors such as VMT and congestion. Nevertheless, it can be

assumed that as the penetration rate of intelligent vehicles increases, the emissions will be reduced.

- **Introduce a life cycle approach:** A weakness of AVs is their energy-intensive production. The construction process of AVs must therefore become greener, which can be encouraged by the government (Petella et al., 2019).
- **Avoid negative effects, and promote positive ones:** Measures should be introduced that lead to a decrease in negative effects such as low (Mensing et al., 2013) or variable (Khondaker & Kattan, 2015) speed limits or to actively promote the positive effects due to AV lanes (Chen, 2015), which enable the platoon technology.
- **Low emission zones:** “A low emission zone (LEZ) is an area from which vehicles emitting pollutants over a given threshold are restricted access to, e.g. hybrid vehicles may be allowed, but internal combustion vehicles would not be” (Mounce & Nelson, 2019, p. 18).

Studies show that AVs will reduce the space required for roads and parking in the long term. This freed public space can be used for other purposes. Assuming that land can be newly used, researchers come to different recommendations regarding how to use this land. Harper et al. (2018) and Zhang et al. (2018) propose opening new parks or housing spaces, whereas Faisal et al. (2019) recommend to enlarging the commercial development.

- **Modal shift away from car:** The use of green spaces for pedestrian or cycle paths leads to fewer people driving (Mounce & Nelson, 2019). Public transport can also be expanded and automated, which leads to a decrease in parking spaces (Soteropoulus et al., 2018)
- **Smart charging infrastructure placements:** Cities must ensure that the charging infrastructure is used wisely to reduce space (Yi et al., 2018).

6 Conclusion

This paper has reviewed existing studies and investigated the impact of AV implementation. It started by demonstrating that today's traffic is reaching its limits and has negative effects on cities and the environment. It also clarified the extent to which AVs can contribute to improving this situation. It has discussed different studies that predict the impact of AVs and combined them to provide the most accurate possible statement. Accordingly, it has particularly focused on how the corresponding KPIs are

influenced. A study from this perspective on the question of whether AVs can solve today's traffic challenges had not previously been conducted.

The results indicate that AVs are a promising opportunity to improve the traffic situation and thus contribute to overcoming the current burden. However, the literature review also shows that there is a risk that the traffic situation will deteriorate. For this reason, chapter 5 has provided recommendations on how to use AVs to make them a success. The main challenge is to ensure that the implementation does not lead to increased traffic, because VMTs have a direct impact on other KPIs.

In summary, the studies were reviewed to provide the most detailed existing insight on the topic to date, and the synthesis provided by this paper can be useful for both policy-makers and researchers. The paper is relevant for policy-makers because they can see directly which parameters influence the success of AVs. Furthermore, the paper offers recommendations for the corresponding parameters on how to avoid negative consequences. For researchers, this can provide hints about which aspects of the existing studies would need to be pursued in further depth and which have been neglected thus far and should be pursued in the future.

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Article 2

Assessing the Impact of Automated Vehicles on Cities with Differing Urban Structure

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Abstract

The impact that autonomous vehicles (AVs) will have on urban traffic in different cities around the world will largely depend both the policies and strategic direction of the city and on the unique traits of a particular city such size, population or topography. This article presents a simulation-based comparison between different cities and autonomous vehicle adoption scenarios to understand what aspects of cities lead to positive AV implementation outcomes, and what aspects lead to negative outcomes. The analysis represents a first attempt to explore the impact of AVs at a large scale across different cities around the world. By simulating different scenarios-along six key performance indicators (KPIs)-on how AVs influence today's cities, the goal is to explore which cities benefit the most from AVs. For the analysis, city archetypes are formed by clustering different cities into categories and selecting a statistical city for each archetype. These archetypes are comprehensive in that they account for most, if not all, world cities. Using these city archetypes, a simulation is carried out for the different scenarios, taking into account the KPIs. The main finding is that cities with differing urban structure see different benefits and drawbacks from the introduction of AVs. While results vary for the different city structures considered, AV-shuttles have positive consequences for all city types. Based on these findings, we provide long-term political guidance on appropriate policy decisions relating to AV introduction in different city types.

Keywords

shared autonomous vehicles, traffic simulation, continuous space modelling, urban mobility

1 Introduction

The idea of autonomous driving is as old as the invention of the car. As early as the 1930s, General Motors introduced a self-driving concept car and in the 1980s, there were concrete plans and systems that were to enable vehicles to drive on their own (Bullock et al., 1983). In the 2010s, the hype about autonomous vehicles grew with the development of lidar (Levinson et al., 2011) and visual recognition systems (Geiger & Lenz, 2012). Nevertheless, nowadays the doubts about AVs have grown and their impact on cities and the traffic situation is questioned. Therefore, it is important to develop a realistic picture of how AVs can really help the world's metropolises.

Today's cities are facing challenges such as congestion, which is represented in vehicle miles travelled (Fagnant & Kockelman, 2015; Farhan & Chen, 2018; Loeb & Kockelman, 2019; Patella et al., 2019), safety (Chen et al., 2016; Wadud, 2017), emission (Grumert et al., 2015; Patella et al., 2019), and urban space (Yi et al., 2018; Gelauff et al., 2019; Malokin et al., 2019). Hence, sustainable reform in urban mobility has become one of the key challenges that policymakers and urban planners around the world are facing (Dia & Javanshour, 2017). One approach that some policymakers are taking is to look for new solutions and long-term strategies for cities to address the current state of urban congestion (Nieuwenhuijsen & Khreis, 2016; Sengupta & Popovich, 2019). In this context, AVs are regarded as one possible technology that may prove to be part of a multi-faceted approach to solve urban congestion challenges. Looking toward the literature, several publications investigate the potential positive effects of AVs based on simulations. One common finding is that the improvement of traffic safety is a major advantages of AVs. Based on simulations, Khondaker et al. (2015) conclude that AVs reduce the probability of collisions by up to 9.8%. Further, Grumert et al. (2015), Patella et al. (2019), and Jones and Leibowicz (2019) state that AVs have a positive effect on the environment and can reduce cycle greenhouse gas (GHG) emission by up to 60% (Patella et al., 2019, Stern et al., 2019). Moreover, AVs might be able to free urban parking spaces (Zhang et al., 2015) and reduce mobility cost (Chen et al., 2016; Abe, 2019; Loeb & Kockelman, 2019). Nevertheless, the introduction of AVs can also lead to undesirable side effects to be expected that eventually cause a worsening of the city-level metrics mentioned above. Le Vine et al. (2015) and Simoni et al. (2019) for example, found that AV could increase travel delays and congestion, while Harb et al (2018) found an 83% increase in vehicle miles travelled with AVs, further burdening the urban infrastructure.

One important observation is that there is substantial uncertainty in the literature with regards to the potential impacts of AVs. As seen in Figure 1, depending on the study, the change in vehicle miles travelled as a result of AVs being introduced ranges from a decrease of 35% (Childress et al., 2015) to an increase of 341% (Harb et al., 2018). Similarly for per-mile AV usage cost, estimates vary between a per-mile reduction of 89% (Boesch et al., 2018) and an increase of 4% (Boesch et al., 2018), while estimates for the number of traffic collisions range from a decrease of 90% (Fagnant and Kocklman, 2015) to an increase of 16% (Davidson & Spinoulas, 2016), and the projections for emissions range from a decrease of 96% (Brown et al., 2014) to an increase of 173% (Brown et al., 2014). These differing model projections from different studies indicate that there is great variability in the potential outcomes of the introduction of AVs into the traffic flow.

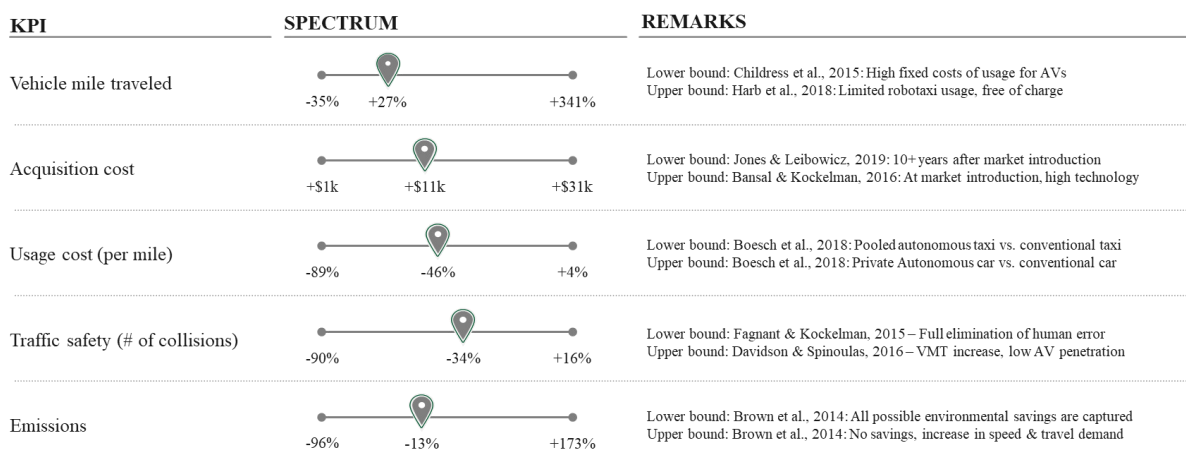


Fig. 1.: Uncertainty in the literature - high variability in simulations for the KPIs considered due to different parameters, cities and scenarios.

One limiting factor is that most studies are spatially limited to specific cities. To our knowledge, only a few studies have considered more than one city while simulating the impact of AVs. A few notable examples of cross-city comparison studies include the studies of Edwards et al. (2018) that consider the impact of cooperative intelligent transport systems across seven European cities, the work of Kroeger et al. (2018) that compares AV impacts in the US and Germany, and the study of Spieser et al. (2014) that considers fleet sizes mechanisms and financial implications for Singapore and the US.

Another limitation of the literature is that most studies focus on the impact of AVs with respect to one parameter such as emission, parking area, or vehicle miles traveled, etc. Only a few studies consider multiple parameter based on simulation results. For

example, Harper et al. (2018) considered the parameter vehicle mile traveled, environmental and needed infrastructure while Fagnant and Kockelman (2014), and Liu et al. (2017) also analyzed multiple parameters. However, each of these studies only consider a single city, Seattle, Singapore and Austin, respectively.

Finally, there is a need for studies that provide a comprehensive strategic plan on how cities should orientate themselves with regard to their mobility concept for the future. Since many studies focus on specific aspects of AV deployments, the recommendations that result provide only a limited set of suggestions for policymakers without providing a holistic understanding of how AVs will influence traffic in different cities. Jones & Leibowicz (2019), for example, limit their policy recommendations only towards realizing a sustainable charging infrastructure, whereas the work of Zhang et al. (2018) solely proposes measures to limit vehicle miles travelled. While each of these studies provide valuable insight into the specific aspect addressed, a comprehensive overview is needed to provide holistic guidance for how to prepare for the autonomous future.

Hence, a study is missing which considered the impact of AVs across a large spectrum of cities along of different parameters. Since it is to be assumed that cities on an international level differ significantly in terms of characteristics such as infrastructure design or vehicle-based travel patterns, the transfer of knowledge from these studies is only possible to a limited extent. This work addressed that gap in the literature and provides a comprehensive simulation-based study to look at the impacts of AVs on multiple key performance indicators (KPIs) for a range of cities. Specifically, this work is based on two underlying hypotheses which explain why AVs can have both positive and negative effects. Specifically:

Hypothesis 1: Every city is unique in its history, size, and population. These unique traits of a city give each city a unique urban structure and make different forms of transportation more suitable for any given city. Thus, the impact of an integration of AVs will be different in each city. However, it is unclear how this urban structure influences the success of a potential AV deployment. Furthermore, it can be assumed that AVs are not equally suitable for every city. For example, Simoni et al. (2019) stated that the vehicle miles traveled will increase by 16-22% in the city of Austin, whereas Patella et al. (2019) stated that the range of additional vehicle miles traveled lies between -5% to +8% in Rome, Italy.

Hypothesis 2: Many studies conclude the success of AVs is mainly influenced by policymaker, as they have a significant role to play in shaping the impact of AVs

(Anderson et al., 2014; Clark et al., 2016; Enoch, 2015; Fox, 2016). To unleash the potential of AVs, a strategic action plans on the part of the urban decision-makers is required (Giduthuri, 2015). Even more, Perra et al. (2017) stated that the configuration of urban transportation is one of the key planning functions of policymakers and an integrated and sustainable approach requires proactive involvement. Since there is no general plan, it is important to understand what places are best suited for AVs. To the best of our knowledge, there have only been a few studies conducted, which analyse the impact of autonomous vehicles on a large scale across different countries and draws long-term recommendations for action. Fagnant & Kockelman (2015), stated that policymakers should begin supporting research into how AVs could affect transportation and land use patterns, and how to best alter our transportation system to maximize their benefits while minimizing any negative consequences of the transition to a largely autonomous fleet of motor vehicles. According to Gavanas (2019), international literature is not yet sufficiently concerned with the challenges around planning the implementation of AVs appropriately.

This research is a first attempt to explore the impacts of AVs at a large scale across cities with different urban structure. By simulating different scenarios of how AVs influence today's cities, the goal is to explore, which cities benefits the most from AVs, and how AVs should be allowed to be deployed to realize that benefit. This question will be answered by using a traffic simulation software that can simulate urban traffic and the use of AVs in the network. First, 40 globally distributed cities are selected and clustered based on a number of different metrics (e.g., city population, city size, city age, etc.). These factors are used to identify different underlying urban structures that can help explain the potential for successful AV deployments. We focus primarily on following research questions:

- Which city type is best suited to autonomous vehicle deployment as measured by factors such as traffic volume, fatalities, transportation cost, parking area, energy consumption, and journey time?
- How should a city strategically align itself with respect to AV deployments based on that city's unique urban structure?

The remainder of this article is outlined as follows. Section 2 focuses on the methodological background of the research. It characterizes the traffic simulation including the creation of clusters, scenarios and underlying assumptions. The results from the simulation are presented in section 3. Implications and recommendations for

policymakers are demonstrated in section 4, while final conclusions are drawn in section 5.

2 Methodological approach

This study applies a traffic simulation approach in the form of a space continuous modelling tool to evaluate the effects of an AV introduction on a global view. Although every city is unique in its history, size, and population, we divided the cities into clusters with similar characteristics. For each of these generated clusters, we simulate the effects of AVs along four different scenarios. We use six key performance indicator (KPIs) to measure the impact of AV introduction: traffic volume, annual fatalities, energy consumption, total parking area, transportation cost, and average journey time. The scenarios applied, represent future scenarios on how cities could develop. Based on the results along the cluster, we derive statements about which scenario will be the most advantageous one for cities. Furthermore, recommendations for action on how to implement AVs successfully are given by cluster, which result in long-term strategic policy plan.

Archetype creation

We select 40 cities with varying geographic distribution, heterogeneity of environment, dominating type of transport, and level of innovativeness. In order to identify the 40 cities, a long list of several hundred metropolitan cities across the world is compiled. Then, we remove cities which have a similar characteristic to other prioritized cities, cities with limited data availability and cities with fewer than 500.000 inhabitants. We then define eight quantitative input criteria which are used for city clustering. The clustering criteria include congestion time (Inrix, 2019), route time (different sources, such as Moovit (2019), or Eurostat (2016)), mode mix (EPOMM, 2019), population density (Demographia, 2016), land use concentration, urban development pattern (extracted from Google Maps), and city age (different sources such as the world fact book (Central Intelligence Agency, 2019) and city specific information such as from Berlin.de (2019)). A K-means clustering method (Hartigan et al., 1979; MacQueen, 1967) is applied. Based on iterations we identify that a class of 5 shows the best match for clustering. Using the attributes for the global cities we apply this unsupervised machine learning approach to group similar cities which have the most different characteristics between groups. To make the clusters even more detailed, a manually adjust positioning of cities is executed based on descriptive criteria such as topography, population size, public transportation cost, and public transportation coverage. As a

result, the 40 cities are divided into 5 clusters which we call archetypes. High-compact middleweight represents cities in which most of the population live within a well-defined central area. Population density are above average and inhabitants use a broad range of transport modes, with demand evenly distributed across options. The car-centric giant represents an automobile-dependent archetype, which generally have large populations but very low population density. It is defined by a large geographic area, dispersed population, and underdeveloped public transit network and has a densely populated center as well as smaller low and medium-density satellite hubs. The prosperous innovation center represents established cities that have developed over an extended period, with low population growth and average density. Several medium-density hubs are contained within the city boundaries. The street pattern is irregular and thoroughfares are often narrow. Inhabitants use a range of transport modes equally. Deveoping urban powerhouse are modern metropolises that are growing rapidly and have a high population density. This archetype is made up of multiple distinct hubs which are clustered along a coastline or river. Most inhabitants currently use public transportation. High-density megacity are relatively modern city that has grown strongly over the past century. It has a large population, with a high-density hub at its center surrounded by densely populated satellite hubs. The archetype is typically located on a coastline. Its streets are generally configured in a grid pattern. Inhabitants use a range of transport options at present. Table 1 shows the result and details of the archetypes.

Table 1

Presentation of the cluster analysis results – Archetypes and their characteristics

	High-Compact Middleweights	Car-Centric Giants	Prosperous Innovation Centers	Developing Urban Powerhouses	High-Density Megacities
City examples	Berlin Vienna	Detroit Toronto	London San Francisco	Bangkok Buenos Aires	New York City Shanghai
Size¹ [km²]	2,300	8,500	5,000	4,000	10,800
Population	8,300,000	4,800,000	5,600,000	9,500,000	24,300,000
Centralization	Very compact city	Strong decentralization	Mixed types	Decentralized cities	Mixed types
Modes	Distributed mix, with focus on public transit	Car centric cities	Distributed mix	Public transit focused	Evenly distributed mix
City age	Mixed types	Mid aged cities	Old, established cities	Newer cities	Mixed types

¹ Includes urban area and periphery**(Space-) continuous modelling**

The purpose of a simulation is to represent the environment in an appropriate way. It is intended to model a real-life or hypothetical situation on a computer so that it can be studied (Lovas, 1994). By changing variables and implementing different scenarios in the simulation, conclusions can be drawn from their impact on the initial situation. However, the aim is a sufficiently accurate representation of the traffic situation under changed framework conditions (Bando et al., 1995). To reflect the impact of AVs on cities the BCG Gamma travel demand simulation model was used. Gamma is a subsidiary of the Boston Consulting Group which focuses on applying data science, analytics and artificial intelligence. The model is mostly based on NHCRP report 716 on travel demand forecasting (Bhat, 2012) and works along five technical steps (Figure 2). These five steps are performed individually for each archetype. The synthetic simulation depicts a typical day within each cluster.

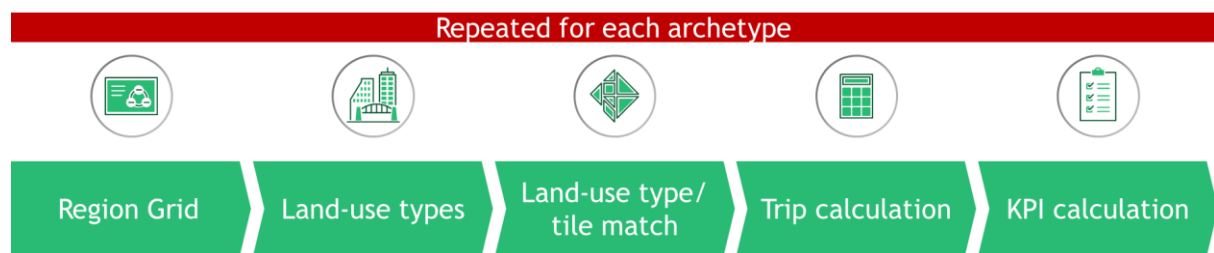


Fig. 2.: Five step modelling process to generate key performance indicator based on the region grid, which is separately applied to all five archetypes.

In step 1, region grid, the entire area of each modeled cluster is separated into equal tiles, each one square kilometer in size. This region grid creates a representative virtual city for each archetype based on the data from the cities within the cluster. Second, Land-use types, in total 13 standardized land- types are created to model different city layouts and their underlying characteristics such as residential, employment or shopping (Figure3). For each of the land-use types, several underlying characteristics are defined that influence mobility behavior. Hereby, employment rates, school enrollment, household income or household size are used as characteristics. Step 3, assigns land-use types to each of the tiles based on preferential urban design. These three steps result in an individual archetype design for each cluster (Figure 3). This design is averaged from the data of the cities located in the cluster. For example, in High-Compact Middleweights, people live within a well-defined central area, making this archetype compact whereas developing urban powerhouses have a high population density which are placed at multiple distinct hubs.

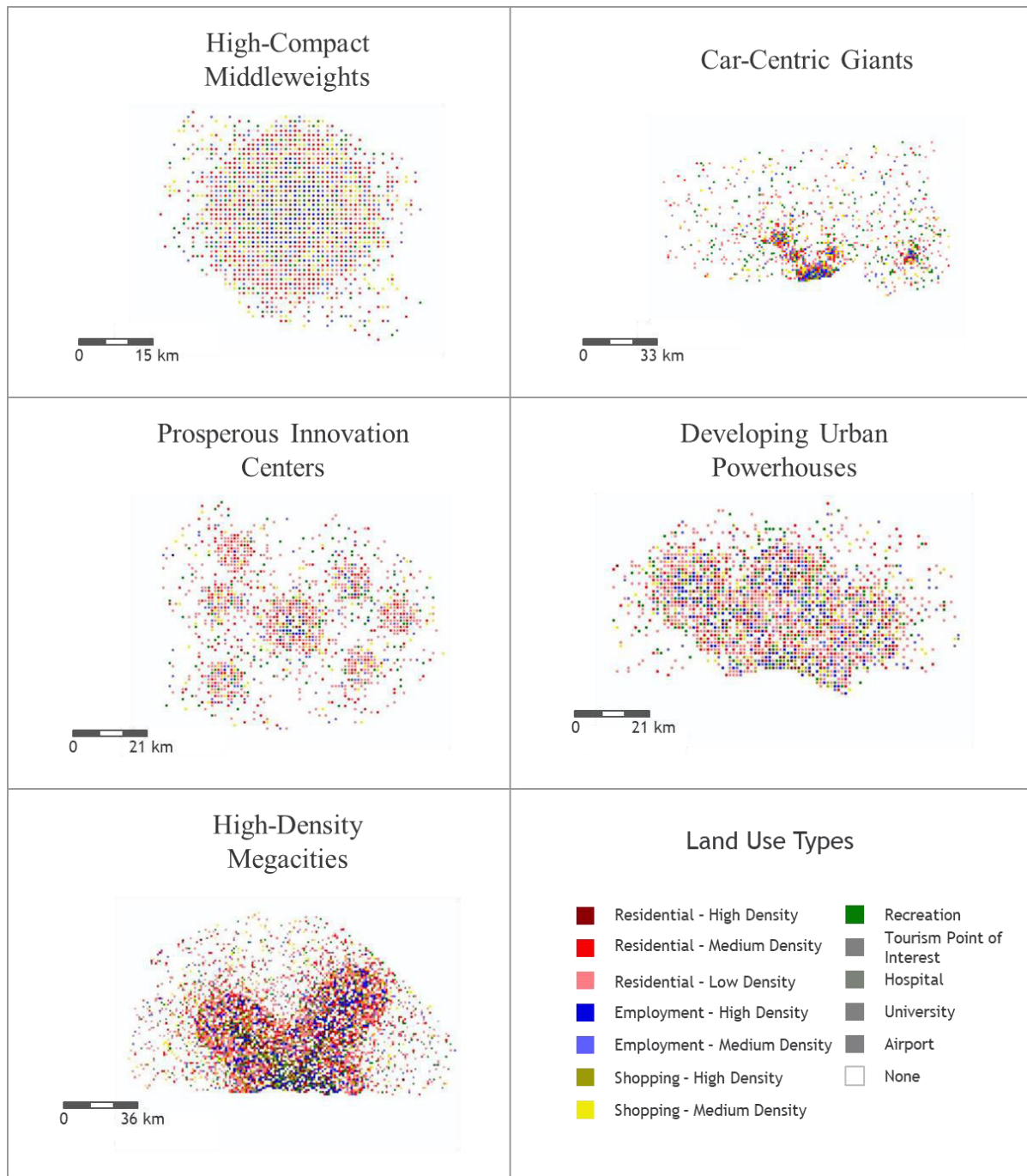


Fig. 3.: Depiction of archetype region grid including land use types which are based upon the clustering of 40 cities.

In step 4, a travel demand model takes the land-use type allocation as an input to calculate transit volume per traffic mode which is represented in number of trips. The method applied in this report follows the conventional sequential process for estimating transportation demand that is often called the “four-step” process: Trip generation, trip distribution, mode choice, and assignment.

- **Trip Generation:** Based on the defined land-use types inputs (Step 1-3), we can assign the number of *productions* and *attractions* for each tile of the grid. Productions initiate trips which originate at this tile and attractions which are destinations for trips ending at this tile. Information from land use, population and economic forecasts are used to estimate how many trips are made to/from each zone. Trips can be home-based or non-home-based, as illustrated in Figure 4.

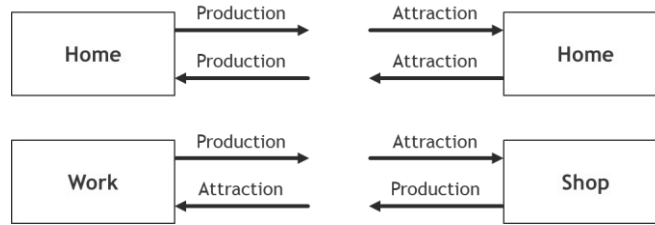


Fig. 4.: Travel Demand Forecasting and Techniques (Bhat, 2012) used to generate predicted demand for simulation.

- **Trip Distribution:** Depending on the allocation of land-use types across the grid, we can simulate the distribution of trips within and across all tiles. It is the step that links the trip productions and trip attractions for each zonal pair. Three steps are necessary to calculate the trip distribution:
 - 1) Estimation of distance between tiles' centroids based on the assumption of the traditional grid network. Friction factors are inversely related to spatial separation of zones. It decreases with the increase of travel times.
 - 2) Calculate denominator of the gravity model for each production:

$$T_{ij} = P_i * [A_j * \frac{F_{ij}}{\sum A_k F_{jk}}]$$

where, T_{ij} = the number of trips from zone i to zone j

P_i = the number of trip productions in zone i

$A_{j,k}$ = the number of trip attractions in zone j , any other zone k

$F_{i,j,k}$ = the friction factor relating the spatial separation between zone i , zone j , any other zone k .

- 3) Estimation of distance between tiles' centroids based on the assumption of the traditional grid network (only north-south, and west-east connections).
- **Mode Choice:** Modal split is a fixed, distanced-based assumption for all tile connections for each scenario. Hence, the mode choice differs among scenarios - explicitly described in the section Modal Mix.

- **Trip Assignment:** Route assignment allocates trips between an origin and destination by a particular mode to a route. This step is covered in the mobility tool at a detail of a tile. This means there is no reallocation of traffic routes, as the trip is assumed to take place on straight lines between neighboring tiles.

Based on the number of generated trips due to the demand model, the transit volume for each transport mode is derived. Based on the transit volume the following KPIs are derived for each cluster in step 5: annual fatalities, energy consumption, total parking area, transportation cost and average journey time. The input parameter from Table 2 has been used for the simulation and the derivation of the KPIs. These parameters were calculated as an average across the values of different countries to reflect a global value. For example, handbooks for technical data were used to calculate energy consumption and average costs. For public transport, data from MVG Munich (MVG, 2019) was used and for AV-shuttles technical data from the manufacturer Navya (Navya, 2019). The number of average deaths refers to how many deaths are caused by the specific mean of transport. The numbers are based on published data by the government of each city or country. We used data from Transport Accident Commission (TAC, 2019) for Australian cities, or data from Transport for London (2019). The occupancy rate is derived from different sources across the world such as from the National Household Travel Survey (NHTS, 2018) by the Federal Highway Administration, or data from the European Environment Agency (European Environment Agency, 2016).

Table 2

Simulation input parameter as average across different cities

Modes	Walking	Micro-mobility	Private car	Public transit	Taxi	AV-Pod	AV-Taxi	AV-Shuttle
Average speed [km/h]	5	15	25	15	25	25	20	15
Average energy consumption [kwh/km]	0	0.02	0.36	14.3	0.36	0.18	0.33	0.68
Average deaths [deaths/billion km]	0	1.3	6.3	33.9	6.3	1.3	1.3	1.3
Average occupancy [pax]	1	1	1.5	81	1.4	1.2	1.6	5
Average cost [\$/passenger km]	0	0.29	0.55	0.25	1.34	0.5	0.51	0.37

Scenarios

A scenario-based approach has been chosen, which covers the most likely relevant trends in future mobility. In total, four scenarios are considered:

Shift from private cars to non-AV transport modes: Although the private vehicle defined the past century to a large extent and a world without cars is hard to imagine, metropolitan authorities introduce policies that curb private car trips and encourage other forms of transport. Several major cities, including Amsterdam, Hamburg, Helsinki, Madrid and Oslo, have already started to restrict the use of cars. Other cities like Bogota, Brussels, Chengdu, Copenhagen, Dublin, Hyderabad, Milan and Paris have different measures that aim at reducing motorized traffic including implementing car free days (Cathkart-Keays, 2015).

Dominance of micromobility: Micromobility is a term used to describe a novel category of transportation using non-conventional battery powered vehicles (standing scooters, also known as electric scooters or e-scooters (SAE International, 2019)) designed for travel over distances that are too close to drive or utilize public transportation, yet too far to walk (Krizek, 2019). Micromobility solutions are not a fad since they rapidly expanded across the world and are present in currently 350 cities (Rose, 2020).

Strong push for AV-shuttles: We identified several companies which manufacture AV-shuttles such as Navya and Easymile. At least 34 other companies such as Bosch, ZF Friedrichshafen, Continental or Daimler are also working on this technology. Furthermore, these types of vehicle are already used in pilot projects in about 20 countries. This scenario represents that in the future autonomous vehicles will be used in a pooled way and not as individual transport even possessed by people.

Strong uptake of AV-pods: Nevertheless, these are smaller autonomous vehicles that require a little less space and are only occupied by 1-2 people. The Occupancy is much lower, because in this scenario you don't share the vehicle with someone else. There will be routes that are not worth driving with shared vehicles or people simply do not want to share vehicles. Tesla for example, is gradually introducing more technology that will allow the vehicle to drive completely autonomously. This would lead to a scenario that is mainly driven by autonomous individual traffic.

Transportation modes

To make the simulation as realistic as possible, single mode trips as well as multi-modal trips were considered. In the simulation of the base case only non-AV trips were considered, while in the future scenario the transport modes were supplemented by AV modes. Multi-modal trips represent the fact that people do not use only one mode of transport. They are much more intermodal and the travel chain contains several transport modes. The used transport modes and multi-modal trips are shown in Figure 5.

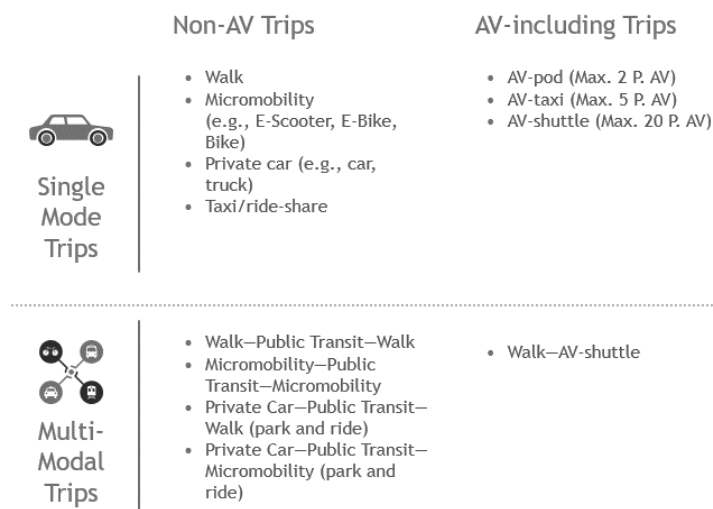


Fig. 5.: Both single mode trips and multi-modal trips are considered in the simulation. Representation in the graphic of the used transport modes and multi-modal transport chains.

Modal mix

With each virtual archetype, we used publicly available data from our city sample to model the modal split today. For the current modal split, we included five transport modes (private car, public transport, taxi/ride hailing, micromobility, and walking). This information forms the starting point for our simulation. For this, we use the findings of a joint study by BCG and the World Economic Forum (Moavenzadeh & Lang, 2018) which asked 5,500 inhabitants across multiple types of city what transport mode they would choose given eight choices. To the five existing options, we add three AV modes: AV-pods (which seat up to two passengers), AV-taxis (up to five passengers), and AV-shuttles (up to 15 passengers). The resulting future modal split is our base case scenario. For the actual simulation, we take into account the distribution of mobility options across short, medium, and long-distance trips using current data and

the results of the BCG/WEF survey (Moavenzadeh & Lang, 2018). Since the study considers only three archetypes and not all transport modes we consider, the modal mixes have to be adapted. For this purpose, a reclassification of the BCG/WEF mode is applied to adopt modal mix to our transport mode logic. The modal mix used for the base case 2018 and the future base case 2035 in our study is shown in Table 3. The numbers indicate how the distribution of the means of transport is divided. To create the respective modal mix for each scenario, the modal mix is adjusted based on the future modal mix base case. For this purpose, the corresponding means of transport that experience an uptake were significantly increased. The modal mix distribution for each archetype and scenario is depicted in Figure 6.

Table 3

Modal mix derived from Moavenzadeh & Lang (2018) for current and future share of transportation

Archetypes	High -Compact Middleweights	Car-Centric Giants	Prosperous Innovation Centers	Developing Urban Powerhouses	High-Density Megacities
<i>Current modal mix</i>					
Public transit	23	12	19	29	21
Private car	31	58	33	22	25
Taxi / Ride hailing	4	6	9	22	22
Micromobility	15	11	9	6	6
Walking	26	13	30	32	26
<i>Future modal mix base case</i>					
Public transit	14	10	15	20	16
Private car	18	31	15	10	12
Taxi / Ride hailing	1	4	4	3	10
AV-pod	3	11	9	2	8
AV-taxi	9	11	11	9	10
AV-shuttle	12	8	8	12	9
Micromobility	18	10	12	14	11
Walking	25	12	27	30	24

**Fig. 6.:** Future modal mix per archetype and scenario aligned with the determined future modal mix which is derived from Moavenzadeh & Lang (2018).

3 Model results

In this section, the results of the quantitative model are presented. First, the results are discussed in general terms, followed by the results of the individual archetypes.

The changes in KPIs are presented in Figure 7; these allow comparing the performance of the KPIs for the different scenarios. For each KPI, we show the performance change to the base case scenario which represents the traffic condition in 2019.

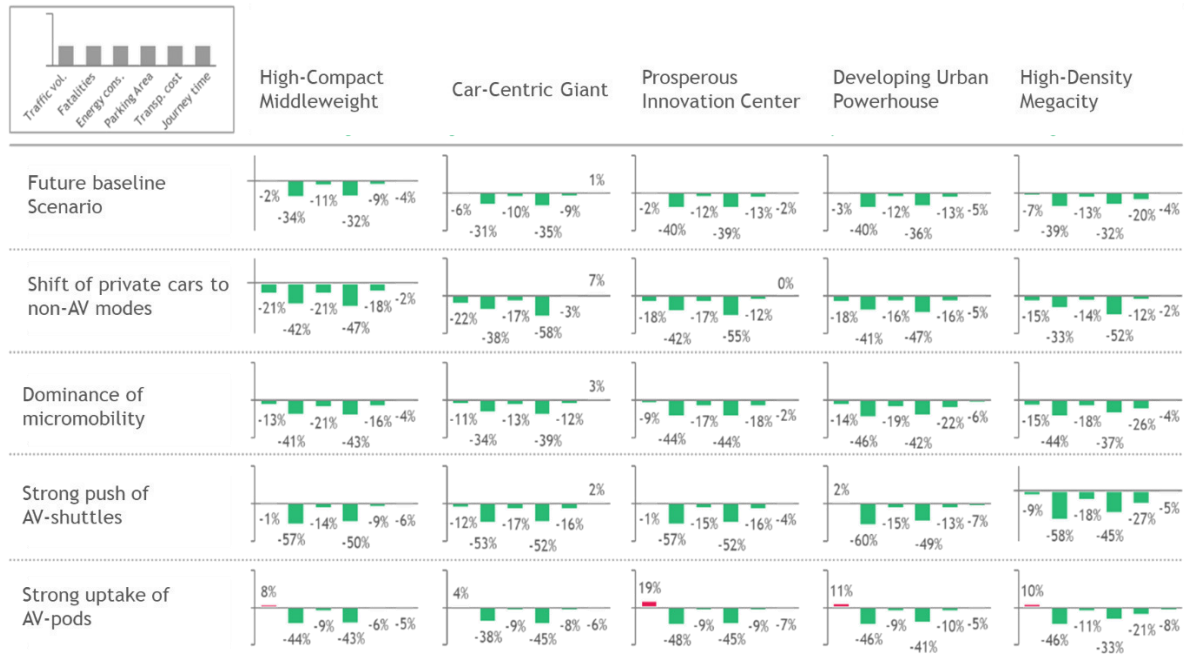


Fig. 7.: Simulation results showing change in traffic volume, fatalities, energy consumption, needed parking area, transportation cost, and journey time for each of the five scenarios applied to each of the five city archetypes.

From this set of KPIs, the most significant result is the improvement of KPIs practically across all archetypes and scenarios. Overall, these results indicate an improvement in traffic conditions (in terms of the KPIs considered) due to an implementation of AVs independent of the scenario compared to a non-integration of AVs. Transferred to the scenarios with the most significant changes, this means a reduction of up to 22% in traffic volume, 60% fatalities, 21% energy consumption, 58% parking area, 27% transportation cost and 8% in journey time across different archetypes. Only in the strong uptake of AV-pods scenario, an increase in traffic volume (up to 19%) is observed. This scenario therefore has the least positive influence. The reason for this is the low occupancy rate and the persistently high level of individual traffic. In relation to our hypotheses, this means that cities benefit differently from AVs depending on their unique traits. Thus, for certain types of cities, there are scenarios that have a better

impact on the city of the future than an AV spread. As politicians today have the opportunity to influence the strategy of their city, they have an impact on the success of AVs. Furthermore, the introduction of AVs must be controlled by politicians. If they are introduced as AV pods, the situation will not improve as much as if AV shuttles are introduced within cities. This statement applies to all archetypes.

Results per archetype significantly vary by scenario

High-Compact Middleweights profit the least from the introduction of AVs - for both scenario strong push for AV-shuttles and strong uptake of AV-pods. The relatively low improvement when pushing for AV-vehicle is due to the characteristic of this archetype by a large number of short trips, a dense city center and good access to public transit. However, AV-shuttles and AV-taxis cannibalize public transportation which leads to a relatively poor improvement in traffic volume: -1% for strong push of AV-shuttle and +8% for strong uptake of AV-pod scenario. The best suited scenario for HCMs is regulating private cars. This scenario performs best for this archetype, as the traffic volume drops significantly with -21% due to the existing infrastructure which can absorb the change from private cars. The high reduction of transportation costs is due to the fact that people change from the more expensive private transport to cheaper public transport.

Car Centric Giants only moderately profit from the introduction of AVs. Although AV-pods offer a convenient and fast replacement of private cars that is greener, cheaper and safer and decreases journey time, transportation remains mainly individual, which weakens the improvement in relation to other scenarios and even leads to an increase in traffic volume due to cannibalization of walking and public transit. However as public transit access is poor, many people in a scenario without autonomous cars switch to taxi / ride hailing, which weakens the positive effect and especially keeps transportation cost reduction low. Nevertheless, the best scenario for CCGs is a strong push of AV-shuttles since missing alternatives in the widely distributed urban pattern can be compensated by these new emerging vehicles. Given this scenario, disproportionately high reduction in parking space (52%) and reduction of fatalities (53%) lead to the best positive changes compared to the basecase scenario.

While AV-shuttles deliver the greatest positive impact for Prosperous Innovation Centers, they also benefit significantly from curbing private cars and encouraging other non-AV transport modes, including micromobility. The advantages result from the high reduction in parking space (up to 55%) and the decrease in parking spaces (up to 57%).

In addition, the traffic volume is greatly reduced (-18%) in the scenario shift of private cars to non-AV. The scenario Strong uptake of AV-pods has the worst effects with a 19% increase in traffic volume. In addition, 9% reduction in transport costs and 9% in energy consumption is this scenario below the improvement of other scenarios.

Developing Urban Powerhouses benefit strongly from a strong push of AV-shuttles, but the scenario dominance of micromobility is of greater advantage. In the strong push of AV-shuttles scenario, the change in fatalities (-57%) and required parking spaces (-52%) is substantial. In the dominance of micromobility scenario, all KPIs perform consistently well, which is why this scenario also has a strong added value. This is particularly due to the fact that good access to public transit is very well complemented by micromobility and replaces private cars. Further, the high share of short trips even allows micromobility to offer a faster journey. Even though a strong uptake of AV-pods leads to a fast journey time as streets dominated by AVs allow a smoother traffic flow, the shift from today's shared transportation to individual transportation increases traffic volume (+2%) and weakens the positive effect of energy consumption, required parking area and transportation cost.

High-Density Megacities profit the most from the introduction of AV-shuttles which present an excellent option for evenly distributed short, medium and large distance journeys. Significantly high improvement is observed as shared autonomous mobility replaces private cars and taxi/ride hailing and simultaneously fosters walking- this eliminates the high costs of individual transport which is replaced by the lower costs of the use of AV-shuttle. While private cars are nearly extinct, with only 10% of trips being conducted by such vehicles. The high share of AV-shuttles & AV-taxis need charging spaces, which lower the effect of the reduction in needed parking slightly compared to the dominance of micromobility scenario.

4 Implications and recommendations

For High-Compact Middleweights, a shift from private cars to other non-AV forms of transport creates the best overall outcome based on the KPIs considered in this study. As seen from the simulation, cities benefit the most, if planners prioritize measures that reduce car volume in urban cities. Since mass-transit networks will pick up the slack by carrying more passengers, it is not prioritized to introduce AVs. AVs should be used in a much more regulated way where the public transportation network ends, or where access to public transport is limited. To do so, planners could introduce measures that define regulatory levers (such as congestions pricing, road closures during peak times,

and high parking fees) which will strongly reduce individual motorized vehicle traffic. But to avoid public transit becoming overcrowded, planners will need to invest in additional routes and new ‘hybrid’ public transport, such as on-demand public buses. Furthermore, it may be advantageous provide last mile options for high number of short trips. For example, agencies could partner with leading last mile providers to set up a sustainable urban mobility plan with them that includes micromobility as main mode of transport.

Promoting AV-shuttles is the best choice for Car-Centric Giants. Public transit networks are often poorly developed in CCGs and cannot absorb additional traffic. According to our simulation, KPIs improve the most, when politicians adapt their strategy to a rapid spread of AV-shuttle. In this case, journeys are bundled which reduces the traffic volume on roads. In addition, the use of AV-shuttles increase access to the public transport network by offering flexible routes, which leads to an increased use of public transport. Hence, preventing overload of public transit due to an extended existing public transit offering (higher frequency, modernization of means of transport, higher accessibility) before shared autonomous vehicles are ready seems to be quite important. Furthermore, implement micromobility only as niche solution. Micromobility with lowest benefits for this archetype due to high amount of medium and long-distance trips in CCGs – city decision makers should limit application of micromobility as first/last mile option in city centers to increase attractiveness of public transit.

While AV-shuttles deliver the greatest positive impact for Prosperous Innovation Cities according to our KPIs, they also benefit significantly from curbing private cars and encouraging other non-AV transport modes, including micromobility. Planners should adopt a balanced approach that promotes all three. As seen in our data, PICs such as London and San Francisco have narrow streets and ageing architecture. Planners should consider curbing private cars in urban centers and creating car-free central zones that favor AVs. They can also build AV-friendly infrastructure, such as dedicated lanes and sensors to help this new technology succeed. They should run AV pilot projects in zones with simple street patterns before venturing into areas with more complex configurations.

For Developing Urban Powerhouses, micromobility promises the greatest benefits. Cities within these archetypes reveal good access to public transportation as well as dense city hub surrounded by satellites. Facilitating an uptake in micromobility will

improve affordability and access. Hence micromobility is a key part of urban transport. Building docking bays and parking areas close to mass transit stations and creating attractive subscription models combining micromobility with public transport (such as free last-mile trips for annual mass-transit pass holders) are two ways to do this. Developing a single booking platform and end user interface will further encourage use of these modes. But planners can also reduce collision rates by creating exclusive micromobility lanes. Many DUPs, such as Bangkok, suffer from disorganized transport systems, underinvestment, and low-tech mobility equipment. AV-shuttles should be treated as a long-term goal to be realized once these deficiencies have been addressed.

As High-Density Megacities derive the maximum benefit from AV-shuttles, they should start introducing them early. Planners can run pilots to create consumer acceptance, trial incentives that encourage switching, and solve problems that could delay a wider roll-out. As small AVs will deliver far fewer benefits, it's imperative that policymakers encourage AV-shuttles and AV-taxis over AV-pods. HDM city dwellers take a relatively high proportion of long-distance trips, so planners should create dedicated AV-shuttle lanes that facilitate these longer journeys and ensure that other vehicles are not hampered by slower-moving, shared AVs. We expect AVs to replace conventional taxis and ride-hailing services in HDMs, so city authorities need to prepare for this transition and the impact on the taxi industry.

5 Conclusion

By carrying out a continuous space modelling approach, this study provides an overview of how an AV introduction effects different cities across the globe. The analysis includes data from 40 cities with eight different characteristics such as urban settings, population density, or model mix. Based on these data, five city archetypes are identified, to which each city is assigned via clustering. For each archetype, five simulation scenarios are performed to determine which scenario is best suited.

The key findings highlight that AVs do not deliver the same benefits to every city. City types with well-developed public transport and small travel routes benefit little from the spread of autonomous vehicles. For such city types, a reduction of individual traffic such as traditional cars lead to the highest improvement of the traffic situation as the public transport network can absorb the additional transport users. Cities with poorly developed public transport systems benefit most from the spread of AV shuttles, as these extend access to the existing public transport network and thus relieve the roads. Densely populated cities with a high number of inhabitants and large areas also benefit

from AV-shuttle expansion. AV-pods are not advantageous in any of the archetypes. The low occupancy of AV-pods leads to an increased load on the transport network.

This paper presents a framework of archetypes to help policymakers better align their long-term strategy for urban development. Policymakers on a national and regional level are urged to revise and adjust their transport strategies to avoid detrimental effects. However, most officials are not prepared to react appropriately (Thomopoulos & Givoni, 2015; Faisal, Yigitcanlar, Kamruzzaman & Currie, 2019).

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Article 3

Exploring the Financial Implications of Operating a Shared-Ride Autonomous Vehicle Fleet in Zurich

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Abstract

Implementing autonomous vehicles (AVs) has many advantages. The main advantages are achieved when AVs are offered as on demand services by a fleet operator. However, autonomous mobility on demand (AMoD) will be distributed nationwide only if fleet operation is economically profitable for the operator. This paper proposes a microscopic approach to modelling two implementation scenarios of an AMoD fleet, differing in fleet size of AVs. The city of Zurich is used as a case study, with the results and findings being generalizable to other similar European and North American cities. The data are based on the traffic model of the canton of Zurich (*Gesamtverkehrsmodell des Kantons Zürich (GVM-ZH)*). A macroscopic approach using the PTV MaaS Modeller tool is used for the simulation. To determine financial profitability, demand is based on the simulation results and combined with analyzing the costs of an AV per kilometer. The results demonstrate that depending on the scenario journeys can be offered profitably to customers for CHF 0.44 or CHF 0.52 per kilometer. While larger fleets allow for lower price levels and increased profits in the long term, smaller fleets exhibit elevated efficiency levels and profit opportunities per day. The paper concludes with recommendations for how fleet operators can prepare themselves to maximize profit in the autonomous future.

Keywords

autonomous vehicles, autonomous mobility on demand, fleet provider, microscopic traffic simulation

1 Introduction

The implementation of autonomous vehicles (AVs) will significantly change our cities and urban mobility. To date, it is uncertain whether AVs will be owned by individuals — and used as upgraded conventional vehicles — or offered as autonomous mobility on demand (AMoD). For city officials and policymakers, privately-owned vehicles, due to low occupancy rates and limited transport capacities, may not be desirable. Such vehicles lead to high traffic loads, which result in congestion (Wang et al., 2013), harmful pollution (Nieuwenhuijsen & Khreis, 2016), and an increasing number of traffic collisions (WHO, 2018). Cities such as Paris, Hamburg, Madrid, and Oslo have recognized these patterns and recently started to ban individual traffic from their streets (Cathkart-Keays, 2015). Also, from the perspective of mobility users, vehicle ownership is an outdated, albeit widespread concept. Factors such as high acquisition costs (AAA, 2019; Becker et al., 2019) and low utilization (Bates & Leibling, 2012) make owning a vehicle unattractive.

Recently, the idea of the sharing economy has entered the transportation sector, fostering the reduced usage of privately owned vehicles (Barbu et al., 2018). Mobility on demand (MoD), as offered by transportation network companies such as Uber or Lyft, provides access to vehicle-based mobility, yet without the responsibility and financial burden of ownership (Boysen et al., 2019; Hamari et al., 2015; Hyland & Mahmassani, 2020). Over the next few years, however, AVs may further disrupt today's MoD concepts. Once AVs are introduced into the market, the sharing aspect will be amplified, enabling the transition from MoD to AMoD (Ciari & Becker, 2017; Meyer & Shaheen, 2017).

AMoD combines automation technologies with one-way vehicle sharing. Sharable AV networks are deployed by fleet operators in a geo-fenced area to serve a wider group of unassociated people, who are picked-up and dropped-off at a desired location upon request (Dia & Javanshour, 2017; Pavone, 2015). AMoD follows the same principle as conventional ride-hailing or taxi services, except that autonomous technology makes such fleets driverless. This leads to higher efficiencies at a fraction of the operating costs, meaning that such services could be offered at the price of public transport (Boesch et al., 2018). The fact that partially overlapping trip requests are matched through dynamic ride-sharing and that rides are pooled among users might further increase the transport capacity of AMoD vehicles. Hence, a single AMoD vehicle can serve the demand of, and thereby replace around, ten non-shared vehicles (Fagnant & Kockelman, 2018). As a result, the number of vehicles on the streets could be reduced

by more than 90% without major tradeoffs in terms of waiting or driving time (Bischoff & Maciejewski, 2016). This could help to counter many of the pressing issues confronting urban areas (e.g., traffic congestion or emissions) or even free up parking spaces, which would no longer be required (Soteropoulos et al., 2018).

Overall, current research suggests that the use case for AMoD holds great potential for urban areas (Milakis et al., 2017). However, AMoD operators might face new challenges: While the current business model of transportation network companies is fairly lean, as vehicles are owned by drivers, operating an AMoD fleet requires vehicle ownership. This results in a continuous financial commitment, including not only operational expenses but also major investments in the vehicle fleet (Chen et al, 2016, Fagnant & Kockelman, 2015). Hence, the question arises whether operating an AMoD system is viable for fleet operators (Gurumurthy et al., 2019; Loeb & Kockelman, 2019). This question remains crucial as such fleets will be rolled out — and thus benefit cities — only if operation is financially profitable (Spieser et al., 2014).

Some researchers have touched on the cost of AVs and their application within cities as AMoD systems (Chen et al., 2016; Spieser et al. 2014). However, additional research is needed to fully understand how AV fleets might be operated from the financial perspective outlined below.

First, only few publications have so far comprehensively addressed the financial implications of AMoD systems from an operator perspective. Even fewer studies have taken into account whether fleet operation is financially profitable. Following the literature, Burns et al. (2012) and Spieser et al. (2014) have discussed the financial implications of the costs of AVs. However, these studies have not considered fleet operations. Fagnant and Kockelman (2018) contrasted the cost of an AV with its return on investment for AV operations in a shared context. Further, Farhan and Chen (2018), Chen et al. (2016), and Loeb and Kockelman (2019) focused on the fleet operator perspective to assess the impact on performance and the cost of different vehicle types. However, these mentioned studies assume a simplified fee structure and do not directly compare operating costs and profit. While Boesch et al. (2018) pointed out inconsistencies and neglected cost buckets in previous studies, they only considered AMoD fleets as one of many potential modes. Hence, they did not explore profit opportunities in detail and their discussion of the strategic implications for potential fleet operators was limited.

Second, previous studies have often involved the same data sets, models, and cities. Hence, results have been biased toward certain geographic areas such as the commonly used Austin region in Texas, US (Fagnant & Kockelman, 2014; Farhan & Chen, 2018; Zhao & Kockelman, 2018; Loeb & Kockelman, 2019). Since cities may be assumed to differ significantly on the international level in terms of certain key characteristics (e.g., infrastructure design or vehicle-based travel patterns), the insights of previous studies may be transferred only to a limited extent. This explains, for instance, that only few studies have investigated AV costs from a European perspective.

Third, simulated demand has often been based on fleet sizes that are derived depending on demand. This procedure allows drawing conclusions about the fleet sizes required to serve a certain number of passengers. However, this results in a significant number of AVs in the network. Chen et al. (2016), for example, simulated more than 57,000 AVs, while Spieser et al. (2014) modelled up to 300,000 AVs. Considering forecasted AV adoptions, such fleet sizes will only occur in far-distant scenarios and are solely relevant to scenarios in the distant future. This circumstance restricts the meaningfulness and practical relevance for fleet operators, as travel demand is likely to fundamentally change until then.

Finally, given the speed of development in the industry, most of the calculated values used in the studies reviewed above have since changed. For example, battery replacement costs have declined significantly over the years.

To date, a study which considers the costs, price, and potential profits of an AMoD fleet in a comprehensive, yet up to date manner is missing. Nor has any study yet examined the financial perspective based on a realistic and relevant AMoD simulation — i.e., first, with fleet sizes that are likely to occur in the near future and second, in a European hub (which would enable transferring the findings and implications across multiple cities). Our study is therefore the first to explore how an AV implementation strategy affects operator profit. This aspect remains crucial as it determines whether the advantages of AVs as shared fleets might eventually become economically and politically viable. Consequently, we conducted a macroscopic traffic simulation in the canton of Zurich, Switzerland. In order to depict different implementation strategies, we modelled the supply side in Scenario 1 with 500 shared AVs and in Scenario 2 with 10,000 shared AVs. Following various AV market share predictions (Archambault et al., 2015; McKinsey & Company, 2016), these fleet sizes may be considered realistic within the foreseeable future. Our simulation involved applying dynamic ride-sharing

mechanisms. This enabled identifying not only the vehicles but also the rides shared by users. It also allowed measured partially overlapping trip requests in real time and considering a set of predefined matching criteria (e.g., maximum detour factor). We comprehensively derived the AV cost structure for both scenarios as well as adapted and updated the results of previous research to produce the most relevant results.

Our overarching research question is: *How does fleet size affect the profit of AMoD fleet operators?* We raise two specific research questions:

1. At which price level can an AMoD service be offered based on a per kilometer view?
2. What are the strategic implications of fleet size for operators?

From a managerial perspective, our approach provides an ideal starting point for exploring the financial implications of realistic AMoD deployment in a representative European hub. Its size, infrastructure, and economy make the city of Zurich a typical major urban area in central Europe. Thus, our results and recommendations may be transferred to other urban hubs of comparable size and role. Furthermore, our study takes into account the most up-to-date information, values, and cost developments.

The remainder of this article is structured as follows. Section 2 illustrates our methodological procedure. It addresses the underlying traffic simulation and highlights the relevant aspects of our cost derivation. Section 3 presents the results of the simulation and cost derivation. Section 4 discusses the results and implications while Section 5 draws conclusions and considers avenues for future research.

2 Methodological approach

This study involved using a traffic simulation of an AMoD fleet across the city of Zurich and its metropolitan area in order to perform a financial analysis. Our methodology comprises two approaches: 1) Simulating demand to gain insights into AV usage and load factors; 2) comprehensively deriving the costs of operating an AV within an AMoD fleet. We assumed a business-to-consumer service model in which the operator is also the fleet owner (Stocker & Shaheen, 2017).

2.1 Simulation-based determination of operational parameters

The transportation simulator PTV MaaS-Modeller was used to simulate the on-demand ride pooling fleet. This tool enables exploring key performance indicators and thus helps to outline an effective business case for operators and cities to plan and control

AMoD implementation (PTV Group, 2017). The simulation runs on PTV Visum, a macroscopic travel-demand simulation software (Noekel & Schaefer, 2018). The PTV Group incorporates algorithms from the logistics industry through PTV X-Server, a logistical and geospatial software for optimizing logistics processes (Noekel & Schaefer, 2018; Barceló et al. 2018). The network in our study is an adapted version of the calibrated and comprehensive traffic model of the canton of Zurich (Kanton Zuerich Volkswirtschaftsdirektion Amt für Verkehr, 2011). Input parameters were fed into the model, and demand calculation and mode choice of the model were iteratively matched with route planning and traffic allocation, in order to determine an equilibrium over the course of the simulated timeframe. Once equilibrium was reached, the output parameters (in terms of vehicle-, passenger-, and further network data) could be retrieved (see Figure 1).

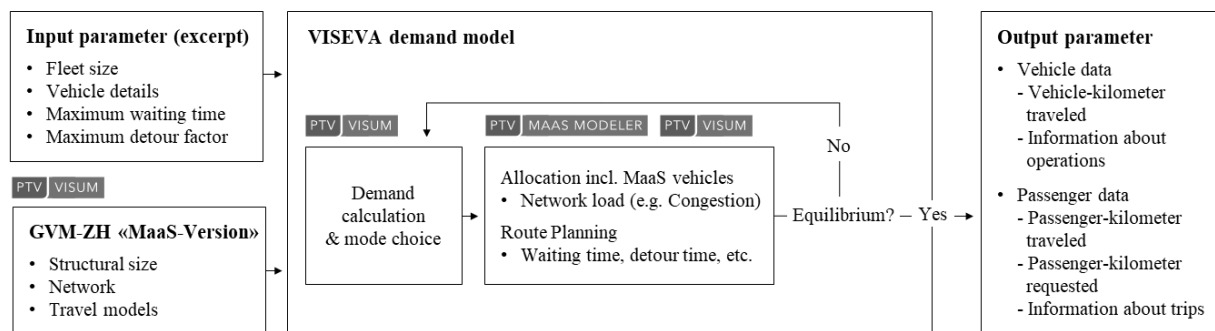


Fig. 1.: PTV MaaS Modeller Workflow showing input and output parameters as well as providing an overview of the demand model approach.

Network and demand model: The network model is based on the multimodal transport model of the canton of Zurich (Gesamtverkehrsmodell des Kantons Zürich (GVM-ZH)) from the reference year 2013 (Kanton Zuerich Volkswirtschaftsdirektion Amt für Verkehr, 2011). The GVM-ZH depicts traffic in its large-scale context (Greater Zurich) and presents its manifestations and interdependencies (demand, capacity utilisation, travel times, etc.). It also includes settlement and structural data (inhabitants, working, sales areas, etc.) and different transport modes. As such, the model represents personal transportation modes and public transport in a single network and also takes into account bicycle and foot traffic in the choice of transport. The GVM-ZH incorporates the transport services of all public transport systems in the agglomeration of Zurich. Consequently, public transit lines with all routes (and their spatial course), as well as stops, transfer points, transport times, and course intervals are recorded. Regarding individual mobility, the model also takes into account the availability of parking spaces at destinations (Vrtric, et al. 2015). In our study, simulated AMoD demand was based

on the MaaS Modeller simulation. Among many other factors, this considers the price, waiting time, detour, availability, and comfort of all potential modes. Figure 2 shows the geo-fenced area within Greater Zurich in which the simulated vehicles operated during our study. At the time, this area comprised 787,538 inhabitants and 373 sqm.



Fig. 2.: Geo-fenced area of Greater Zurich that determined the scope of the AMoD service (shaded grey).

Simulation parameters: While both scenarios were simulated with the same input parameters with regard to, for example, waiting time, maximum detour factor, seat capacity, or charging time, two scenarios were chosen to differ only in AMoD fleet size. The fleet size was set to 500 shared autonomous vehicles in Scenario 1 and to 10,000 shared AVs in Scenario 2. We have used a small number of AVs compared to other studies. Much higher numbers of AVs were considered in comparable studies, such as Chen et al. (2016) who consider a fleet up to 57,000 AVs and Spieser et al. (2014) who consider up to 300,000 AVs. However, like Lindsay & Townsend (2014) stated, a high

number of AVs is not a realistic future scenario, since it will take decades for AVs to be deployed on a larger scale. This approach aimed to explore how potential implementation strategies impact financial considerations. For both scenarios, we assumed that the whole fleet was operated by one transportation company and that corresponding demand was met only by this supplier. Scenario 1, therefore, depicts a slow implementation strategy, with a moderate number of AVs in the network. Scenario 2, on the other hand, follows a rapid growth and scale approach. Most recently adopted by various scooter-sharing services, this approach results in a significant number of transportation units in the network within a short time frame (Schellong et al., 2019).

2.2 Derivation of the comprehensive costs for a vehicle in the AMoD fleet

Overall costs were determined to establish the costs and profits of the fleet within the simulation. This procedure was primarily based on Boesch et al. (2018), yet adapted and updated to allow for the most realistic and relevant results regarding our research questions. Following a comprehensive bottom-up approach, cost components were comprehensively derived based on reference values from practice and academia. The costs considered refer to an AMoD application in the city of Zurich and are given in Swiss Francs (CHF). As some product and service prices are gross, Swiss VAT of 7.7% (ESTV, 2020) was deducted whenever applicable (Boesch et al., 2018).

Investment costs: The most crucial cost factor of an AMoD service is AV acquisition. Given that, to date, no fully autonomous car is commercially available, the vehicle price in our study is composed of an electric vehicle and an automation premium that incorporates the technology to make the vehicle drive by itself. In our study, the Audi e-tron served as a reference point, with a base price of around CHF 70,000 (ADAC, 2019), with the automation premium set at CHF 10,000 (Fagnant & Kockelman, 2015; Jones & Leibowicz, 2019). As AV technology will become cheaper due to learning and scale effects, a 10% learning rate per annum was factored in and the technology was assumed to have been on the market for three years at the time of investigation (Wadud, 2017). A fleet discount of 21% was considered for the 500 vehicle fleet (Blens, 2015) and 40% for the 10,000 vehicle fleet (eFahrer, 2020). Vehicles were assumed to be financed with a loan. Given the confidentiality of corporate interest rates, we performed a multi-step approximation, which considered capital market rates, corporate bonds from fleet operators, and private annuity loans. Credit terms were assumed to be flexible and based on vehicle lifetime (in years). Thus, interest rates were set at 3.5% for Scenario 1 and 2.5% for Scenario 2 (compounded annually). Based on Deloitte (2019), we assumed that AVs have a life expectancy of 300,000 km and that the vehicle price

is written-off linearly over the kilometer-based life expectancy. Potential processing fees and cash-flow relevant repayments were neglected. In the case of the canton of Zurich, municipal taxes were waived (BFE, 2020). Since the warranty of the electric battery of most electric vehicles is limited to a maximum of 160,000 km (Autogazette, 2020), and following Chen et al (2016), the AV battery must be replaced once in a lifetime. According to the ADAC (2019), the battery capacity of the Audi e-tron amounts to 71 kWh. With battery packs becoming significantly cheaper every year (Loeb & Kockelman, 2019), the mean values of battery cost predictions for 2025 were adopted and rounded to CHF 110 per kWh (Lutsey & Nicholas. 2019). A fleet discount was granted as stated above, and battery installation was calculated with CHF 100. Vehicle registration, including the registration certificate and number plate, amounted to CHF 100, but was rounded up to allow for potential administrative compensation (STVA, 2020). As great uncertainty exists about AV insurance premiums (Loeb & Kockelman, 2019), vehicle insurance was set at CHF 800 per year (Comparis.ch, 2018). Given that further savings may be expected due to AV crash avoidance (MacKenzie et al., 2014; Wadud, 2017), the insurance premium was reduced by 25%. Moreover, fleet discounts of an additional 10% and 20% respectively were granted. Boesch et al. (2018) established Overhead and Operations costs by determining potential indirect costs (e.g., development and provision of booking infrastructure, real estate, the management team and other personnel, as well as advertising expenses or customer discounts). The values of CHF 14 and CHF 10 per AV per day were adapted for Scenario 1. For Scenario 2, we assumed that scale effects lead to a significant cost reduction of 75%.

Operating costs: While new automation technology will make cars more prone to system failures, service intervals will be significantly reduced in the future due to the electric drivetrain (Firmenauto, 2019). In our study, therefore, the car was serviced and maintained every 30,000 km at a cost of CHF 300 for Scenario 1 (Repcheck, 2020). For Scenario 2, we assumed that vehicle service could be conducted in-house and that the accruing costs could be reduced by 25%. Furthermore, costs for tires must be taken into account (Boesch et al., 2018). According to Pneuexperte (2020), an all-season tire costs around CHF 55 and lasts 50,000 km (Lange, 2020). Volume discounts of 10% and 20% were granted for the two scenarios. To calculate the required electricity to power the vehicles, the fuel consumption of the Audi e-tron with 25.8 kWh per 100 km served as a benchmark (ADAC, 2019). According to Swisscharge (2020), the variable charging costs in the urban area of Zurich amount to around CHF 0.30 per kWh. The variable time tariff and a fixed entry fee were neglected in our calculation to offset potential

savings from agreements with station providers. Furthermore, we assumed that no further infrastructure investments (e.g., private charging stations) were necessary. This assumption was supported by the fact that Zurich City Council actively supports setting up charging infrastructure (City of Zurich, 2019). To address potential parking expenses while the AV is idle, the yearly parking costs of a Drive-Now vehicle of CHF 1,000 were adopted for Scenario 1 (Frankfurter Rundschau, 2017). A 50% parking discount was assumed for Scenario 2, as cities are actively incentivizing the potential reduction of privately owned vehicles (BCS, 2019). Considering that cleaning intervals are highly subjective (Loeb & Kockelman, 2019), a total cleaning time of 10 minutes every 30 passenger trips was factored in and a minimum of one cleaning procedure per day was stipulated. The hourly wage of vehicle cleaners was set at CHF 35 (Quitt, 2020) so as to include the (potential) costs of machinery and cleaning utensils. As vehicle trips were limited to urban space, toll fees were neglected.

Table 1
Overview of cost derivation parameter

	Scenario 1	Scenario 2
Investment costs		
Vehicle lifetime	300,000 km	300,000 km
Base vehicle	CHF 70,000	CHF 70,000
Automation premium	CHF 7,290	CHF 7,290
Vehicle fleet discount	21%	40%
Interest rate	3.5%	2.5%
Battery capacity	71 kWh	71 kWh
Cost per kWh	CHF 110	CHF 110
Replacement cost	CHF 100	CHF 100
Battery fleet discount	21%	40%
Registration	CHF 100	CHF 100
Insurance (per year)	CHF 800	CHF 800
Insurance automation discount	25%	25%
Insurance fleet discount	10%	20%
Overhead (per day)	CHF 14	CHF 3.5
Operations (per day)	CHF 10	CHF 2.5
Operating costs		
Maintenance & service	CHF 300	CHF 225
Service interval	30,000 km	30,000 km
Tire-set	CHF 210	CHF 210
Tire lifetime	50,000 km	50,000 km
Tire fleet discount	10%	20%
Electricity (per kWh)	CHF 0.3	CHF 0.3
Consumption (kWh / 100 km)	25.8	25.8
Parking (per year)	CHF 1,000	CHF 500
Cleaning interval	30 trips	30 trips
Hourly cleaning wage	CHF 35	CHF 35
Time per cleaning	10 minutes	10 minutes

3 Results

3.1 Simulation results

The traffic simulation model in our study determines the crucial parameters of our financial analysis. Regarding a fleet operator's implementation strategy, it is crucial to understand the demand that arises within a city. The demand for Scenario 1 was 244,832 potential trips, while that for Scenario 2 increased by 19% due to improved service availability. The small fleet size in Scenario 1 meant that only 18% of all requested trips were served by the AMoD fleet, while the majority of requests were denied due to

lacking transport capacity. In Scenario 2, however, about 76% of all trip requests were served (see Figure 3). The deviation can be explained by a mismatch of demand and supply, as no empty AV was available at the time some of the requests were registered. Demand followed a typical pattern, peaking in the mornings and afternoons (Zhang et al., 2018). The total vehicle-kilometers traveled per day for the 500-vehicle fleet amounted to 310,172 km (Scenario 1) compared to 1,737,937 km for the entire fleet (Scenario 2).

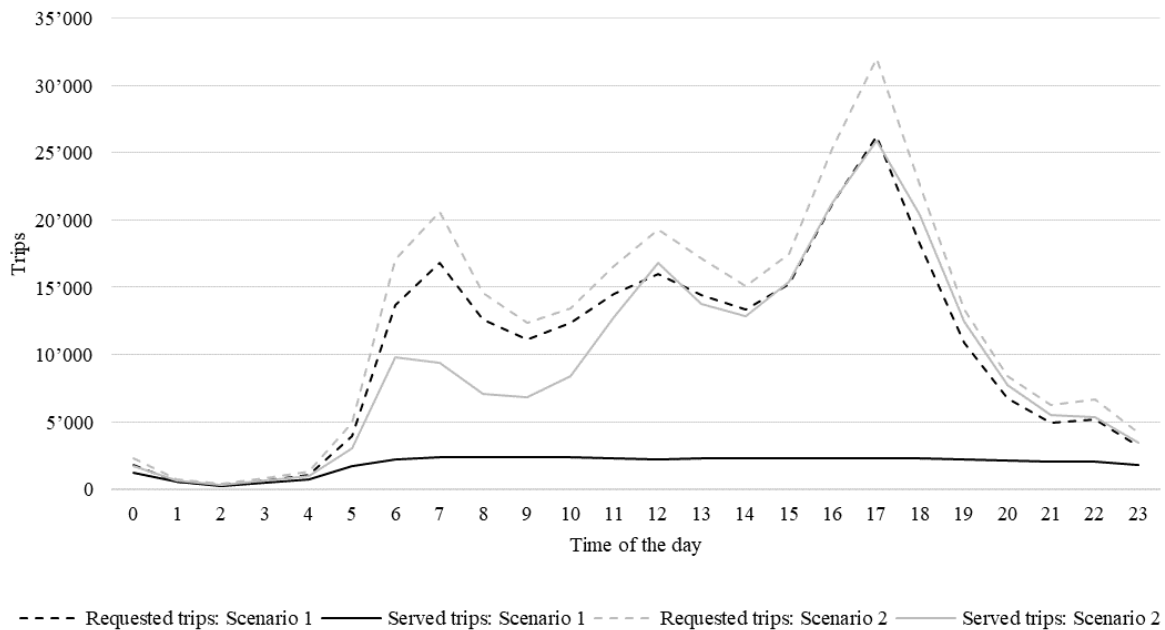


Fig. 3.: Requested and served trips for both scenarios over the course of the day.

Average vehicle occupancy for all occupied vehicle trips was 1,5 people for both scenarios. The relatively low utilization of dynamic ride-sharing can be attributed to the fact that waiting time was limited to 2 minutes. The average trip length for Scenario 1 was 6.3 km, compared to an average of 7.8 km in Scenario 2. The increase in trip length for Scenario 2 resulted from more vehicles being available to serve these passengers. In Scenario 1, by contrast, the relative shortage of AVs led to longer-distance trips with a higher fraction of empty kilometers being forgone in favor of shorter trips in the denser city core.

Table 2

Demand-based output parameters from the simulation for the entire network

	Scenario 1	Scenario 2
Passenger-kilometers travelled (incl. detour) [km]	283,145	1,607,722
Passenger-kilometers requested (excl. detour) [km]	253,558	1,466,481
Number of served trips [trips]	44,667	223,007
Number of requested trips [trips]	244,832	292,525
Average passenger-trip length [km]	6.34	7.79
Number of passengers [pax]	62,356	313,063

Considering the simulation results on a per-vehicle basis, the results suggest that an AV in Scenario 1 drives an average of 620 km, compared to almost 174 km per day in Scenario 2. This translates into average active vehicle times of 22:55 and 8:55 hours, respectively. While, due to excess demand, the 500 AVs in the network are close to full utilization over the course of the day, the 10,000 AVs demonstrate significant downtimes, as vehicles are idling while waiting for new trip requests to be served. Nevertheless, vehicle efficiency increased in Scenario 2, as the empty vehicle-kilometers (9,9%) was lower than in Scenario 1 (10,1%).

Table 3

Supply-based output parameter from simulation for the entire network

	Scenario 1	Scenario 2
Vehicle-kilometers travelled [km]	620.34	173.79
– Occupied vehicle-kilometers [km]	559.06	155.85
– Empty vehicle-kilometers [km]	61.28	17.94
Active Operating Time [hh:mm]	22:55	8:55
Share of empty kilometers driven [%]	10.12	9.88

Figure 4 shows that, in both scenarios, most traffic occurs in downtown Zurich and leads to a higher traffic load in the city center. Consequently, increasing AMoD fleet size does not significantly impact users' route choice or travel patterns. This finding is highly favorable from an operator's business perspective, as trips to more remote areas increase empty driving, as vehicles need to relocate themselves back to areas with more demand in order to serve the next trip requests.

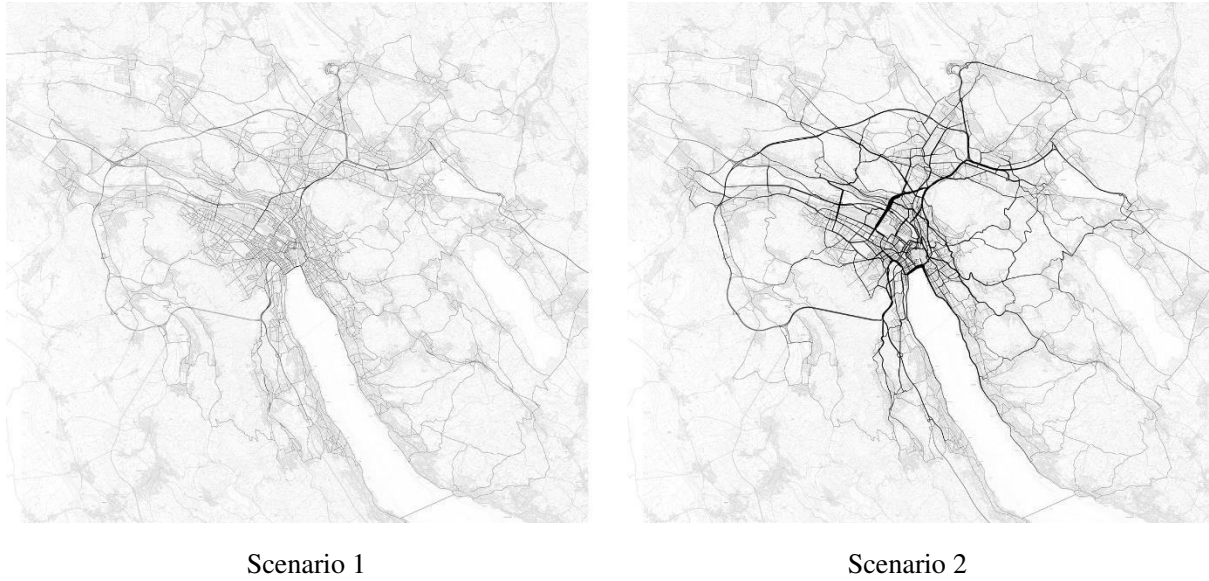


Fig. 4.: Network utilization due to AMoD fleet traffic for both scenarios.

3.2 Financial analysis

Determination of cost per vehicle-kilometer

To consider costs on a per vehicle-kilometer basis, fixed costs (incurred only once in an AV's lifetime) were standardized by the vehicle lifetime of 300,000 km. Costs recurring after a certain distance driven (e.g., vehicle and tire maintenance) were first accumulated for the entire vehicle lifetime before being divided by kilometer-based life expectancy. Daily costs were broken down by the simulated daily vehicle-kilometers as stated above. Regarding annual costs (e.g., insurance or interest), daily vehicle-kilometers per AV and kilometer-based life expectancy were both taken into account. Since, according to the Swiss BFS (2019), the daily travel distance per person is relatively constant across all days of the week, daily usage patterns can be extrapolated to the year (Fagnant et al., 2015). Therefore, fleet operating time was first calculated in years using daily vehicle-kilometers and AV life expectancy, before yearly costs were added up and divided by 300,000 km.

Table 4 shows the resulting breakdown of the corresponding costs per vehicle-kilometer. Based on the analysis, an AV may be expected to operate at CHF 0.37 in Scenario 1, compared to CHF 0.33 in Scenario 2. These figures incorporate potential detours and unoccupied trips. Under our simulated conditions, this figure translates into average operator costs of CHF 231.77 (Scenario 1) and CHF 56.77 (Scenario 2) per vehicle per day, based on daily vehicle-kilometers.

Table 4
Costs per vehicle-kilometer

	Scenario 1		Scenario 2	
	Cost [CHF]	Share of Cost	Cost [CHF]	Share of Cost
Investment Costs				
Vehicle Depreciation	0.189	51%	0.144	44%
Interest	0.006	2%	0.003	1%
Replacement Battery	0.019	5%	0.015	4%
Registration	0.000	0%	0.000	0%
Insurance	0.003	1%	0.007	2%
Overhead	0.023	6%	0.020	6%
Operations	0.016	4%	0.014	4%
Operating Costs				
Maintenance & Service	0.009	2%	0.007	2%
Tires	0.004	1%	0.003	1%
Electricity	0.072	19%	0.072	22%
Parking	0.004	1%	0.007	2%
Cleaning	0.028	7%	0.034	10%
Costs per vehicle-kilometer	0.374	100%	0.327	100%

Determination of price levels

Analyzing potential price levels requires converting costs to a per passenger-kilometer basis. Therefore, we first considered accruing vehicle costs on a per-day basis and subsequently broke these down according to the simulated requested passenger-kilometers. This approach implies that possible detours occurring due to the nature of ridesharing are not charged to the user. Furthermore, we considered revenues by the number of journeys rather than by the number of passengers. This strategy is also adopted by leading MoD services such as Uber Juntos (Uber, 2020) or common taxis in Zurich (City of Zurich, 2015), according to which a supplementary charge is only required from three or four passengers per journey request. The price per passenger-kilometer, P_{pkm} , calculation was performed analogously to Boesch et al. (2018) and by taking into account the Swiss payment transaction fee (p) of 0.44% (WEKO, 2014), VAT, and the cost per passenger-kilometer C_{pkm} , as stated above. To allow for viability, the current median profit margin (r) in the transportation sector of 4.6% (CSI Market, 2020) was applied. In addition, demand in terms of passenger-kilometers requested was assumed to be fixed, implying completely inelastic demand (i.e., unaffected by price changes). Furthermore, no fixed fee (e.g. per ride) was considered; the price level was expressed in terms of a variable kilometer-based fee (Boesch et al., 2018).

$$P_{pkm} = \frac{C_{pkm}}{(1-r)(1-p)}(1+VAT)$$

As a result, feasible price levels of CHF 0.52 per passenger-kilometer were derived for Scenario 1 and CHF 0.44 for Scenario 2. Correspondingly, AMoD can be offered viably at the aforementioned price level while capturing an industry-average profit and considering empty vehicle travel. Adapting the formula below also enables deriving the corresponding margin upon determining a variable price.

$$r = 1 - \frac{C_{pkm}(1+VAT)}{(1-p)(P_{pkm})}$$

As illustrated in Figure 4, under the simulated conditions and assuming inelastic demand, the fleet operator can break even with a price level of between CHF 0.50 (Scenario 1) and CHF 0.42 (Scenario 2). The much lower price for Scenario 2 is primarily caused by fleet discounts, yet is also impacted by longer fleet life expectancy due to fewer trips served per day.

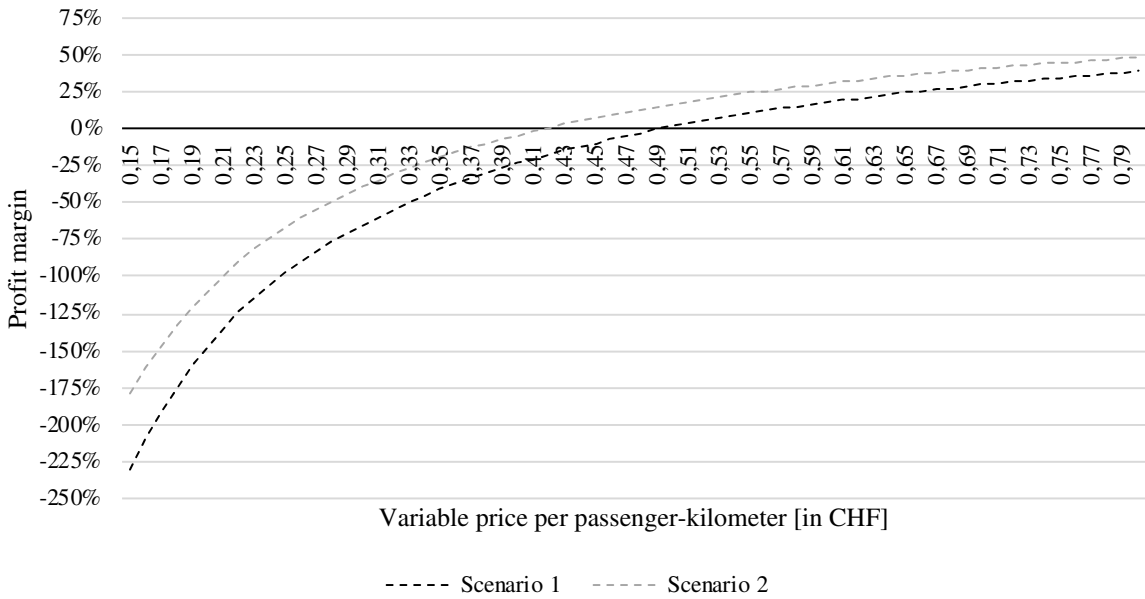


Fig. 5.: Variable prices per passenger-kilometer with corresponding profit levels.

4 Discussion

4.1 How does the fleet size of an AMoD fleet affect profit of a fleet operator?

To evaluate profit in absolute terms, we calculated daily costs by multiplying the costs per vehicle-kilometer with the daily vehicle-kilometers traveled. Analogously, we calculated daily revenue using the feasible price per passenger-kilometer and the

passenger-kilometers requested per day, as stated above. We calculated profit by subtracting daily costs and transaction fees from daily revenue.

$$Cost_{day} = D_{vkm} C_{vkm}$$

$$Revenue_{day} = \frac{P_{pkm}}{1 + VAT} R_{pkm}$$

$$Profit_{day} = Revenue_{day}(1 - r) - Cost_{day}$$

$Cost_{day}$ are the total daily operating costs, D_{vkm} represents the daily vehicle-kilometers traveled, $Revenue_{day}$ is the expected daily revenue, R_{pkm} illustrates the initially requested vehicle kilometers without potential detours, and $Profit_{day}$ is the expected daily profit.

Table 5
Overview cost, revenue, and profit

	Scenario 1		Scenario 2	
	per AV	per Fleet	per AV	per Fleet
Cost per day [CHF]	231.77	115,886.01	56.77	567,743.65
Revenue per day [CHF]	244.02	122,010.65	59.77	597,749.23
Profit per day [CHF]	11.18	5,587.79	2.74	27,375.48

Under the simulated conditions and assuming a feasible price level (see above), operating an AMoD fleet enables generating a profit of CHF 11.18 and CHF 2.74 per AV per day, depending on fleet size and daily kilometers. As, according to Fagnant et al. (2015), mobility usage patterns in terms of passenger-kilometers are relatively constant across all days of the year, daily profit can be extrapolated to the year and results in a yearly profit in absolute terms of CHF 2 million (Scenario 1) and CHF 10 million (Scenario 2), respectively. While the number of vehicles in Scenario 2 is 20 times that of Scenario 1, the costs and the corresponding profit for Scenario 2 are only about 5 times higher. This results from the high deviation in servable trip requests per day per AV. As each AV in Scenario 1 accumulates about 3.6 times as many vehicle kilometers and 4 times as many passenger trips per day compared to the 10,000 AV fleet, the costs and revenues are “accelerated” and vehicle lifetime in terms of years is significantly reduced. While AVs in Scenario 1 will most likely reach their 300,000 km life expectancy within the first two years, AVs in Scenario 2 are expected to be in the market for around five years before reaching their kilometer-based life expectancy. Consequently, while costs on a daily or yearly basis for Scenario 2 will most likely be much lower, they will occur over a much longer time period.

While the analysis shows that operating an AV fleet may be highly profitable, it only considers the fare-based revenue from variable kilometer-based prices. Thus, actual profit will ultimately depend on the chosen price level.

4.2 *Strategic implications for fleet operators*

When determining the size of their AMoD fleet, operators must weigh up achieving cost saving potential and ensuring service quality. Larger fleets result in major discounts, which in turn lower price levels and potentially increase operator profit. In contrast, smaller fleets hold cost saving potential as, due to learning and scale rates, certain cost components are expected to steadily decrease over time. As small fleets reach much higher turnover and thus can be replaced much more frequently, operational assets become much cheaper. On the other hand, the rejection of about 82% of all trip requests in Scenario 1 poses a major problem. While this finding does not affect the present business case, it is highly unfavorable from the customer point of view. Particularly during peak times (mornings and afternoons), excess demand means many trips are not served. The resulting unreliability might lead to other modes of transport being preferred over AMoD. Consequently, fleet operators are advised to determine fleet size whilst keeping both the customer and the operational-efficiency perspective in mind.

Our simulation also shows that given high demand levels, the larger the fleet, the more inefficient the service becomes in terms of served trips per day. This finding stresses the need for ride-sharing to avoid empty vehicle travel, which accounted for about 10% of the driven distance in both scenarios. Consequently, fleet operators are advised to incentivize potential users to share, i.e., pool rides (Martinez et al., 2014). Operators can improve matchmaking algorithms by granting discounts to users who book rides in advance or to those who are willing to wait longer for the AV to arrive. Both actions would enable the system to combine individual journeys more effectively as it gives the technology a time buffer. Moreover, Figure 4 highlights the concentration of traffic in central areas that might not only result in further congestion but potentially cannibalize public transport. This instance will apply particularly when considering competitive AMoD price levels: If customers used AMoD as their sole mode of transportation for the Swiss average daily travel distance of 36.8 km (BFS, 2019), the price of CHF 19.1 and CHF 16.2 for the two scenarios would only marginally surpass the price of CHF 13.6 for a three-zone public transport ticket in the city of Zurich (City of Zurich, 2020), while offering higher levels of convenience. While a conventional taxi would charge more than CHF 200 for this distance (City of Zurich, 2015), AMoD offers vehicle-based mobility at a fraction of the costs. This, in consequence, might lead to conflicts of

interest with policymakers and urban planners, who are likely to introduce countermeasures. Fleet operators should thus aim to improve efficiency on a system level. To ensure financially worthwhile operations, they are advised to cooperate with policymakers, to jointly decide where to introduce the geo-fenced area and also to ensure mobility in areas that lack transportation alternatives. This allows for routes to be subsidized by cities and ensures sustainable operations in the short and long term for fleet operators.

The initial investment of around CHF 28 million (Scenario 1) or over 430 million (Scenario 2) merely to acquire the fleet might challenge many operators. In order to increase profitability and accelerate achieving breakeven, fleet operators are advised to improve operational efficiency. This, however, can only be accomplished profitably if the AMoD service is well used and well accepted by customers. Operators are therefore recommended to carry out pilot projects, to invest in acceptance and trust-building measures, and to create awareness among the population, city governments, and regulators.

Other business opportunities arise beside fare-based revenue. Selling moving patterns, offering in-vehicle experiences, or running advertisements on or inside vehicles provides further means for increasing profitability. Moreover, even a comparably small fleet size of 500 AVs experiences high inefficiencies during low-demand times, particularly from around midnight to around 6 am in the morning. Instead of having cars parked or cruising around empty, fleet operators are advised to utilize vehicles for non-passenger purposes. These might include last-mile goods delivery. Thus, fleet operators should ensure they control in-vehicle experience and explore value-creation opportunities with potential stakeholders. Horizontal collaborative transport offers great potential for making freight transport more sustainable (Pan et al., 2019). Integrating AVs in this context also makes sense from the fleet operator's point of view. Following this proposal, higher fleet efficiencies throughout low-demand times could be maintained and revenue could be further incremented.

5 Conclusion

We used a case study in a major European city (Zurich, Switzerland) to analyze the financial implications of operating an AMoD service and to draw generalized conclusions about the profitability of such system based on demand simulation results. We have adapted, updated, and enlarged Boesch et al. (2018)'s cost analysis of shared AVs to derive an AV's level of cost per kilometer. We have also applied cost analysis to an AMoD fleet operation based on a macroscopic traffic simulation. Our aim was to

establish whether, from a fleet operator's point of view, operating an AMoD fleet is economically viable. Scenario 1 simulated a fleet of 500 AVs compared to a fleet of 10,000 AVs in Scenario 2. These scenarios represent a realistic fleet size within the next five to 10 years in which AVs will expand and complement the existing transport network instead of replacing it completely.

The results show that operating an AMoD fleet of 500 and 10,000 AVs within the city of Zurich is profitable even at low price levels. With an industry-average profit margin, the fleet simulated in Scenario 2 could generate a profit of up to CHF 27,375.48 per day. We also find that the biggest cost driver is vehicle acquisition, which accounts for up to 50% of total operating costs. Considering high AV utilization, AMoD vehicles are replaced roughly every 1.5 years in Scenario 1 compared to every five years in Scenario 2. Therefore, the learning rate, which reduces the cost of manufacturing AVs, plays a crucial role. Consequently, fleet costs will become increasingly cheaper in the following years. We also put the user costs incurred for average daily use of mobility services in relation to other means of transport. The costs of AMoD use are slightly higher than for public transport. They are, however, cheaper than using a conventional personal vehicle or even cheaper than using other mobility services such as micro-mobility, ride-hailing, or traditional taxi services. Based on these results, we recommend various measures for fleet operators, including cost saving, increasing operational efficiency, and pursuing long-term sustainable fleet deployment in collaboration with policymakers.

Both our scenarios are based on 500 and 10,000 shared AVs simulating an AMoD service launch in the next five to 10 years. Needless to say that our simulation approach has various limitations. These include not sufficiently taking into account psychological factors (e.g., lack of acceptance of or trust in AV, which would influence mode choice). Further limitations stem from the cost derivation. Although this study has involved comprehensive research, a certain degree of uncertainty remains about some of the cost components, as it is not yet clear how exactly the system will play out once launched. This, for example, applies to parking costs or overhead and operational costs.

Due to the rapidly developing market, the cost structure of AMoD fleets should be continuously updated in the future. Further research should also include real-world experiments to further evaluate the effect of psychological adoption barriers and price sensitivity on different price functions and on the profit levels of fleet providers.

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Article 4

Preparing Managers for Strategies and Learning about Cities in the Autonomous Vehicle Race

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Time for management to analyze how autonomous vehicles could provide value for different cities.

Today's cities are plagued with substantial growth in populations and jobs, hug traffic delays, and bad driving conditions. These problems with progress in 5G, the Internet of Things, and other emerging technologies, have pushed technology companies and original equipment manufacturer into the autonomous vehicle industry which could change how we think about mobility in cities of the future. How autonomous vehicles will affect future cities is important for upcoming innovators (e.g., Mobileye, Navya, Cruise, Delphi) and traditional car manufacturer (e.g., Volkswagen, Ford, Mercedes, and BMW).

Then, the question is: will autonomous vehicle succeed in future cities? Our short answer is not necessarily, and it's certain that not all vehicles have a role in all cities. Cities are so different.

Over the past few years, extensive management resources have been geared to push innovations for smart cities.ⁱ Most of the traditional equipment manufacturers are committed to bringing autonomous vehicles to cities by 2026 and have invested heavily in autonomous driving and robo-vehicle innovations, such as robo-shuttles, robo-pods, and robo-taxis. Audi, the premium auto brand from Volkswagen, plans to spend close to \$16 billion on self-driving and sustainable tech by 2023.ⁱⁱ Beyond monetary investing, BMW is forming an alliance with Intel and Mobileye to push autonomous driving forward. The alliance will employ 1,200 technicians to promote autonomous driving, with the goal of getting autonomous vehicles on the road by 2024. Companies are investing heavily because they expect a high return on investment. Spending on autonomous vehicles by traditional industry players and newcomers alike is forecasted to grow to a cumulative \$85 billion through 2025—on top of spending for electric vehicles.ⁱⁱⁱ The high level of investment in autonomous technology leads to high expectations of return on investment for companies. Accordingly, the fundamental question arises - will autonomous vehicles work? Given that cities are so different we present in this paper the results of a large-scale research project conducted by the University of St. Gallen and Boston Consulting Group. The study analyzed whether our cities are suited to the smart city concept and the revolutionary technology that enables autonomous driving.

Although it is important to cut down on traffic volume, fatalities, energy consumption, parking areas, transportation costs, and commute times in cities, autonomous vehicles

could cannibalize public transportation and alternative forms of transportation, such as walking. Therefore, even though replacing private cars is greener, cheaper, and safer than keeping them on the road and may decrease commute times, changing modes of transportation to achieve the smart city concept is complicated and risks increasing traffic volume. Interestingly and inarguably, cities differ in factors like population density, land concentration, infrastructure, and urban development, so it may be very difficult to implement autonomous driving in some cities. Amsterdam, for example, is a very active city, with about 60% of people using active forms of transportation, such as biking and walking. Further, Amsterdam is a very old city with historic narrow streets that make individual traffic very unfavorable. In Los Angeles, in contrast, more than 80% of people drive their own car, and the city is a rather new city built for vehicles. Although cities are different, we clustered 40 cities into five archetypes. We can then make statements about how advantageous autonomous vehicles will be for these archetypes.

Despite numerous vehicles are currently being launched and investments into autonomous vehicles are substantial, the majority of innovations related to the smart city concept and autonomous driving may not bear fruit. In fact, we argue that many companies (e.g., Google, Samsung, and traditional original equipment manufacturers) that were early in investing in new mobility and autonomous vehicle solutions may face new challenges when executing their strategies.

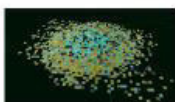
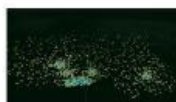
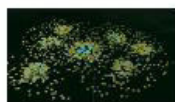
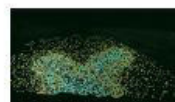
Over the next decade, companies who are working on autonomous vehicles need to develop strategies for cities. The reason? Cities are different, and autonomous vehicles are not the optimum solution for every city's current conditions. To understand how prepared cities are for autonomous vehicles and the new strategic approach management is facing for these large-scale investments, in our research, we modeled the challenges they will likely face when transitioning smart cities to autonomous driving.

Modeling Autonomous Driving in Different Cities

Based on expert interviews with industry leaders, policymakers, and researchers as well as a large-scale database with information on city construction, including exact mappings of city zones, homes, workplaces, etc., we conducted advanced simulations of the consequences of introducing technology innovations related to robo-vehicles in different types of cities. In particular, applying criteria used to cluster cities in prior research, such as congestion time, route time, population density, land concentration,

urban development pattern, and work and leisure activities, we identified five city archetypes, which we used to model the impact implementing autonomous vehicles will likely have for different cities. Figure 1 shows the characteristics of the city archetypes we used to research the value of implementing autonomous driving in different types of cities. To exemplify, highly compact middleweights, such as Berlin and Vienna, have a high population density, and people live within a well-defined central area, making this archetype compact. Developing urban powerhouses, such as Bangkok, also have a high population density, but individuals live in multiple distinct hubs.. Thus, because cities like Berlin and Bangkok are different, the transportation possibilities and its resulting benefits of autonomous vehicles vary significantly between the cities.

Figure 1: Five City Archetypes Form the Basis for the Simulation Tool

					
Examples	Berlin, Vienna	Detroit, Toronto	San Francisco, London	Bangkok, Buenos Aires	New York City, Shanghai
Size¹	<2,000 km ²	3,000 - 6,000 km ²	4,000 - 8,000 km ²	3,000 - 6,000 km ²	6,000 - 13,000 km ²
Population¹	<5 M	3-7 M	2-8 M	7-15 M	15-27 M
Characteristics	Most of the population live within a well-defined central area. Inhabitants use a broad range of transport modes, with demand evenly distributed across options.	Automobile-dependent metropolis, with a large population but very low density. Large geographic area, dispersed population, and underdeveloped public transit network.	Established city that has a low population growth and average density. The street pattern is irregular and thoroughfares are often narrow. Inhabitants use a range of transport modes equally.	Modern metropolis that's growing rapidly and has a high population density. City is made up of multiple distinct hubs which are clustered along a coastline or river. Most inhabitants currently use public transportation.	Modern city that has grown strongly over the past century. City have a large population, with a high-density hub at its center. Streets are generally configured in a grid pattern. Inhabitants use a range of transport options at present.
Simulation result					

1. Includes urban area and periphery; outliers possible
Source: BCG analysis

The simulations are based on a very comprehensive travel-demand simulation model that was tested on data from 40 real cities. The model incorporates city layouts and their underlying characteristics, such as residential, employment, and shopping districts. It also includes several underlying characteristics that drive mobility behavior, such as employment rates, school enrollment, household income, and household size. These characteristics are used to calculate the change in transit volume, number of trips, and mode of transportation (private cars, including motorcycles; public transportation; taxi/ride hailing; micromobility, including bikes; and walking) due to the implementation of autonomous vehicles. To the five existing modes of transportation, we added innovations related to the three autonomous vehicle modes: robo-pods (which

seat up to two passengers), robo-taxis (up to five passengers), and robo-shuttles (up to 15 passengers). Depending on area size, population, and economic forecasts, our tool estimates the distribution of trips and the number of trips made to/from each city zone. The number of daily trips as well as real inputs from 40 cities are then used to derive key performance indicators (KPIs), including annual fatalities, energy consumption, total parking area, transportation costs, and average journey time. Based on this simulation procedure, the modeling was repeated for each archetype and scenario. In total, we modeled 1.7 billion daily trips, which allowed us to compare the suitability of autonomous vehicles for the different city archetypes.

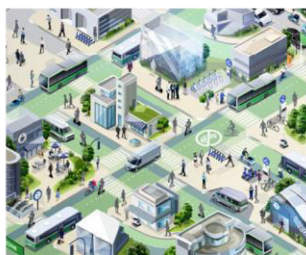
Overall, using this procedure, we investigated how implementing the three types of autonomous vehicles will likely influence cities' existing transportation modes along the defined key performance indicators such as fatalities, energy consumption, total parking area, transportation cost, and average journey time.

How Autonomous Driving Will Influence Our Cities

For the mathematical computations underlying our model, we used a scenario-based approach focusing on the most prominent innovations for future mobility in cities as well as current regulatory frameworks. In total, the simulation modeling considers four scenarios (see Figure 2).

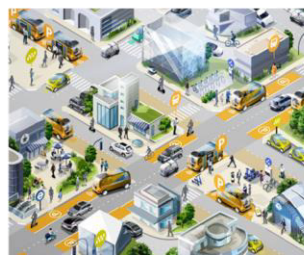
Figure 2: Scenarios Will Play Out Differently Depending on the Archetype

Shift from private cars to non-AV modes



- Metropolitan authorities introduce policies that curb private car trips and encourage other forms of transport.
- Several major cities, including Amsterdam, Hamburg, Helsinki, Madrid and Oslo, have already started to restrict the use of cars.
- Key futures include less parking space for cars, more space for bicycles and an improved public transport network

Strong push for robo-shuttles



- In the future autonomous vehicles will be used in a shared way (on-demand) rather than as individual transport.
- Multiple new players, such as Navya or Easymile are placing a bet on robo shuttles.
- 34 other companies such as Bosch, ZF Friedrichshafen, Continental or Daimler are also working on this technology

Dominance of micromobility



- Micro-mobility, such as standing electrical scooters dominate the transport system.
- Micromobility solutions are not a fad since they rapidly expanded across the world and are present in currently 350 cities.
- E-scooter startups have already attracted more than \$1.5 billion in funding, and BCG estimates that the global market will reach about \$40 billion to \$50 billion by 2025.

Strong uptake of robo-pods



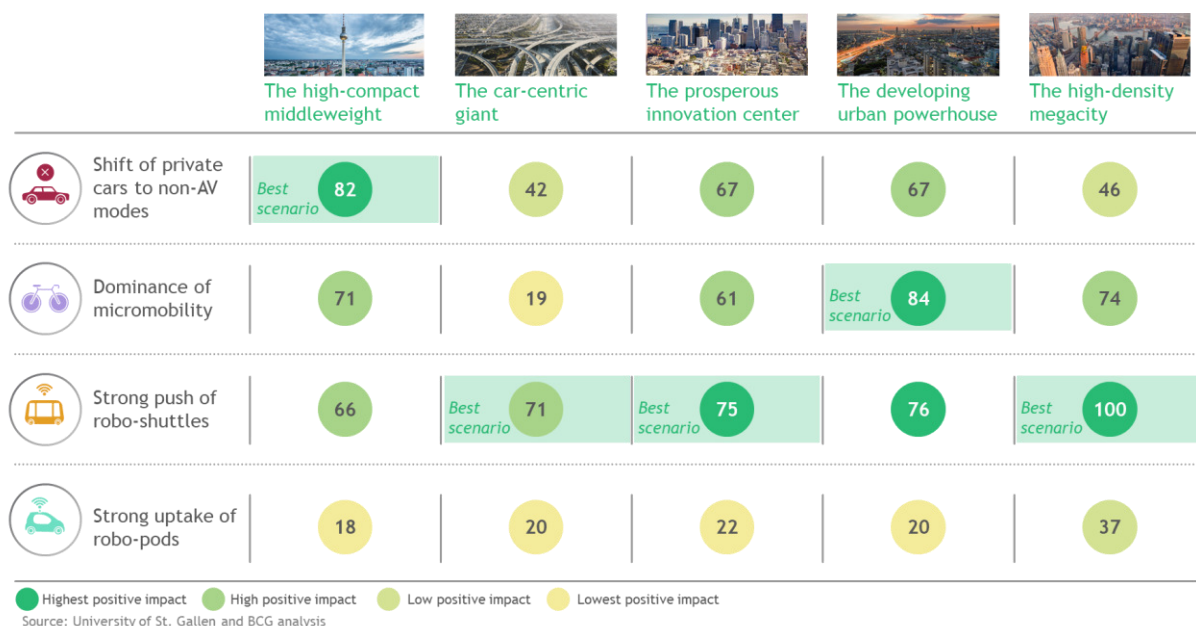
- Autonomous vehicles are mainly used privately in the future.
- There will be routes that are not worth driving with shared vehicles or people simply do not want to share vehicles.
- Customer acceptance increases as they are willing to pay up to \$5000 more for a fully self-driving car.

To understand how cities transportation performance will likely change with the introduction of autonomous driving, we modeled the influence of implementing the

three sets of autonomous vehicles for the above scenarios. We used the previously discussed KPIs—annual fatalities, energy consumption, total parking area, transportation costs, and average journey time. Overall, the results indicate an improvement in cities’ traffic situation (in terms of the KPIs considered) from implementing autonomous vehicles regardless of the scenario. Transferred to the scenarios with the most significant changes, however, this means a reduction of up to 22% in traffic volume, 60% in fatalities, 21% in energy consumption, 58% in total parking area, 27% in transportation costs, and 8% in average journey time. Only in the strong uptake of robo-pods scenario is an increase in traffic volume (up to 19%) observed. Thus, this scenario has the least positive influence due to the low occupancy rate and persistently high level of individual traffic with robo-pods.

To illustrate our findings from the simulations and to identify core principles that can be executed in city transportation strategies, we created a mobility index. This index is helpful for understanding the match between the different city archetypes and the different types of scenarios including autonomous driving vehicles. Based on the mobility index city planners and policymaker can develop city transportation strategies. All scores show a positive impact from implementing autonomous vehicles and range from zero (the lowest positive impact) to 100 (the highest positive impact). We marked the scores indicating a positive above-average impact in darker colors and scores indicating a positive below-average impact in lighter colors (see Figure 3).

Figure 3: The Mobility Index Provides an Overview of the Model’s Results



Shifting from private cars to non-autonomous vehicle modes is the most effective measure to reduce the number of private vehicles within highly compact middleweights. As evidenced, the highly compact middleweights (e.g., Seattle, Vancouver, and Sankt Petersburg) will likely profit the most from this scenario since individual traffic can easily be replaced by alternative transportation modes. These cities likely profit the least from introducing autonomous driving. The relatively low improvement from introducing robo-vehicles is due the large number of short trips, dense city center, and good access to public transit characterizing this archetype. However, robo-shuttles and robo-pods cannibalize public transportation, which leads to relatively poor improvement in traffic volume.

Developing urban powerhouses (e.g., Moscow and Seoul) benefit from the dominance of micromobility scenario the most. Micromobility perfectly complements the high share of short-distance trips and will likely switch people from private cars and taxi/ride hailing to greener, safer, and cheaper transportation modes. Furthermore, micromobility complements good access to public transit very well. Even though a strong uptake of robo-pods leads to a fast average journey time as streets dominated by autonomous vehicles enable smoother traffic flow, the shift from today's shared transportation to individual transportation increases traffic volume and weakens the positive effects of energy consumption, total parking area, and transportation costs.

The strong push of robo-shuttles scenario is beneficial for car-centric giants, prosperous innovation centers, and high-density megacities. Car-centric giants (e.g., Atlanta, Detroit, and Dubai) profit from a strong push of robo-shuttles since missing alternatives in their widely distributed urban patterns can be compensated by these new emerging transportation modes. The disproportionately high reduction in parking space and in fatalities arising from this scenario lead to the best positive changes compared to the other scenarios. Prosperous innovation centers (e.g., Amsterdam, London, and Sydney) are characterized by several medium-density hubs contained within city boundaries. An uptake in robo-shuttles delivers the greatest positive impact as such shuttles connect hubs with each other, thereby reducing parking space and traffic volume. High-density megacities (e.g., New York City, Beijing, and Paris) profit the most from introducing robo-shuttles, which present an excellent option for evenly distributed short-, medium-, and large-distance journeys. Shared autonomous mobility replaces private cars and taxi/ride hailing and simultaneously fosters walking, thus eliminating the high costs of individual transportation in lieu of the lower costs of robo-shuttles.

Strategic Lessons for Management

What the current modeling and our expert interviews with city planners, industry experts, and policymakers reveal is that managers and companies who are investing heavily in autonomous vehicles cannot ignore knowledge about cities. This knowledge is something that risks being ignored, but doing so will prove to be costly. The fact that cities have different characteristics is important to consider when implementing new autonomous driving technologies. As our research shows, along with bringing autonomous vehicles and the required infrastructure into urban environments come a variety of new challenges. As such, an uncontrolled introduction of autonomous vehicles may induce significant deterioration in traffic conditions and even more in social conditions within cities. To counteract these negative effects, not only do policymakers need to put favorable regulations and strategic plans in place, but companies also need to prepare for the future to win the autonomous vehicle race. Based on our research, several lessons come to mind.

Consider what value autonomous driving will offer different cities

According to the 45% share of our expert interviews, autonomous vehicle services may be operated by leading tech companies such as Mobileye, NuTonomy and Waymo. Nevertheless, a lot of other companies such as traditional automobile manufacturers and ride-hailing supplier such as Uber and Lyft will be candidates to be the first operators since they all have autonomous driving strategies in place. One of the first issues managers of these companies should address when considering autonomous vehicles is value proposition. Again, cities are different, so autonomous vehicles do not provide the same added value for every city. Based on our analysis, it will be important for management to acknowledge that the most beneficial scenarios will be different for different cities and that a winner-takes-all scenario may not materialize. For example, a strong push of robo-shuttles is likely the best scenario for highly dense megacities like New York City and Shanghai. In cities like Berlin or Vienna city planners and policymaker should not bet big on autonomous vehicles since their public transportation system is well developed and the benefits from the new transport mode are rather small. Concrete, autonomous driving is not just about new transportation modes. It will fundamentally change cities and will force city planners and policymaker to rethink how their transportation should be reorganized to unleash the highest benefits from autonomous driving. Consequently, companies have to ensure that autonomous vehicles represent added value for cities and its citizens. If there is no added value for cities, the technology will not be accepted by customers or it will be even restricted by

policymakers which means that high investment costs do not yield a return on investment.

Make sure to have a sustainable and forward-looking business models

New business models for mobility are emerging. We are seeing a move from owning a “one-size-fits-all” vehicle toward the use of shared, flexible, on-demand mobility. Thus, managers need to adapt and formulate business as a service models around autonomous vehicles. While car manufacturers with traditional business models only earn about \$0.01 per car per driven kilometer, there is the possibility for fleet operators to earn up to \$0.20 per car per kilometer through an on-demand service. Managers who understand and embrace this trend will benefit from the change in mobility. This means, traditional car manufacturers have to find their place in autonomous vehicle production and supply in a new way. They need to think carefully about the role they want to play, and they need to adjust their current offerings to meet the needs of players and customers in the urban mobility ecosystem of the future, for example, by changing vehicle designs to accommodate new use cases. Also, other stakeholders within the mobility ecosystem must adapt and develop new business models. In example, autonomous driving is an innovation that will disrupt the transportation business as we know it. In the case of New York City, for example, about 14,000 licensed medallion cab drivers and more than 80,000 drivers for the four largest non-taxi ride providers (i.e., Uber, Lyft, Gett/Juno, and Via) need to prepare for slow business according to the experts we interviewed. Alliances with intermediary taxi companies could be alternatives to today's fragmented taxi market.

Experiment, look for win-win partnerships, and engage in collaboration

Autonomous driving presents both a difficulty in developing vehicles and also operating a fleet within cities once the technology is area wide available. To overcome this difficulty, we expect to see a lot of strategic experimentation between stakeholders such as traditional car manufactures, tech-companies and cities. In example, partnering is key to winning the race of developing scalable autonomous vehicle concepts: tech companies need original equipment manufacturer knowhow to build hardware at quality and scale, while car manufacturers need tech-company's know-how to build applications, backends, and data analytics. Once autonomous vehicles are developed and can be offered as on-demand services, it is important for companies to cooperate with cities. Simply offering a mobility platform such as Uber does in 73 countries, will not work with autonomous vehicle services as we can deduce from our simulation.

According to the results of the simulation, cities benefit in different ways from autonomous vehicles and so individual solutions must be found for various types of cities. Hence, cities will set frameworks for implementing autonomous vehicles in such a way that cities profit the most from the new technology. To do so, experimenting what forms of collaboration between the stakeholder are possible is important. Especially in the early stage of autonomous vehicle implantation, there will be no static implication process. Rather the way to realize autonomous vehicles requires a dynamic of all stakeholders. This brings us to the next point, pilot projects to conduct experiments and test partnerships.

Be picky and target the right pilot projects

Trying to compete requires exploration with different pivots. Here, the selection of pilot projects will be particularly important to all stakeholder. Then, pilot projects allow different stakeholders to gain experience at various levels in order to offer autonomous vehicles on a large scale. Furthermore, pilots create awareness for a city's population, government, and regulators. This awareness will be important to engage in a dialogue with the public about any plans to implement autonomous vehicles because citizens will almost certainly be the primary customers in this market. In our expert survey, 80% believe that acceptance can be a barrier if citizens are not involved in the autonomous driving integration process. A good practical example of how to create awareness is the city of Boston which is piloting autonomous driving with three different tech companies—nuTonomy, Optimus, and Aptiv—and one of the key principles of Boston's autonomous vehicle strategy was to involve citizens. Beyond creating awareness, pilots help to adapt the service of the autonomous vehicles to customer needs. Beyond awareness, perhaps the most important decisions will be choosing the appropriate vehicle(s) for each city to implement and determining how cities' initial concepts can be part of a larger expansion process. Making these decisions will ultimately be a question of technologies, partnerships, and knowledge about cities and will entail strategic planning that is quite different from that of today. For example, based on our analyses, for the high-compact middleweights (e.g., Vienna), pivoting would involve a shift from private cars to non-autonomous vehicle modes. Technically, this business model would mean banning private cars in city centers, strengthening existing public transit networks, and providing last-mile options for short trips. Here, the value proposition is to compete by creating seamless intermodal connections for end users by closely linking public transport and last-mile transportation. Such a value proposition will take close collaboration between partners to achieve and could involve

a variety of solutions, including companies only providing last-mile transportation to companies taking full transportation responsibility by teaming up with car providers. Also, car manufactures have the chance to reinvent themselves and engage early in city pilots to test new business cases.

Patience and precision for value capture

It should also be noted that even though numerous companies are competing in the autonomous vehicle race, this race will take time. The payoff for investments will also take time, and forming the right constellation with patience is important for meaningful progress. Companies need to be aware of high initial investment costs and slow amortization. Assuming a city like London needs about 340,000 robo-vehicles (robo-pods, robo-taxis, and robo-shuttles combined) in its metropolitan area, this means an investment cost of \$28.54 billion according to our simulation tool. Beyond investing in an autonomous vehicle fleet, , 90% of our experts think an autonomous mobility on demand-friendly infrastructure has to be in place (e.g., separate lanes for autonomous vehicles, smart signals, curb-space management) before autonomous driving will be seen in cities. This means that pure investing in vehicle technology is not enough. Cities must adapt the existing infrastructure to the new technology. According to the majority of our surveyed experts a legal framework can speed up the introduction of autonomous driving because such a framework will ensure a smooth transition from manual traffic to autonomous driving. While Silicon Valley was first on the track to implement such frameworks, many are now also looking at what is going on in China. Many believe that China may have a strong influence on autonomous vehicle technology, legal frameworks, design, and operations. However, many European and American players are moving to take major stakes here.

To Win, Be Prepared to Learn How to Craft Strategies for Cities

Autonomous vehicles are not a concept without content. They are here and will happen. Companies that do not figure out how to address cities will miss out on the race, and existing vehicle providers will be disrupted by new entrants. Further, existing business models will most likely be obsolete. Although different strategies will emerge in this race, we know one thing: cities will play an important role in the success of autonomous vehicles. It is important to understand cities and realize they are different when crafting the next generation of strategies for vehicle providers and manufacturers more broadly. This issue goes far beyond the car industry, which will of course soon be confronting one of the larger challenges from the last decade.

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