Autonomous, connected, electric shared vehicles (ACES) and public finance: An explorative analysis ☆

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ABSTRACT

This paper discusses the implications of autonomous-connected-electric-shared vehicles (ACES) for public finance, which have so far been widely ignored in the literature. In OECD countries, 5–12% of federal and up to 30% of local tax revenues are currently collected from fuel and vehicle taxation. The diffusion of ACES will significantly reduce these important sources of government revenues and affect transport-related government expenditures, unless additional policies are introduced to align the new technological context with the tax revenue requirements. We argue that the realization of socioeconomic benefits of ACES depends on the implementation of tailored public finance policies, which can take advantage of the increase in data availability from the further digitalization of transportation systems. In particular, the introduction of road tolls in line with 'user pays' and 'polluter pays' principles will become more feasible for policy. Moreover, innovation in taxation schemes to fit the changing technological circumstances may alter the relative importance of levels of governance in transport policy making, likely shifting power towards local, in particular urban, governmental levels. We finally argue that, given the risk of path-dependencies and lock-in to sub-optimal public finance regimes if policies are implemented late, further research and near-term policy actions taken during the diffusion process of ACES are required.

1. Introduction

This paper discusses the case of autonomous connected electric vehicles (ACES), which are the result of four major ongoing techno-economic developments in transportation: *automation* (automated vehicles: AVs), *connectivity* and *digitalization* (connected vehicles or CVs), *electrification* (electric vehicles: EVs), and *shared ownership* (shared vehicles: SVs). These technologies separately, but especially in their combination are expected to lead to major disruptions in the transport market, which has been in a fairly stable technological regime over the past decades (Pinkse et al., 2014; Dijk et al., 2016). Although the pace and shape of the disruptive changes induced by

ACES cannot be predicted accurately at this point in time, there seems to be a consensus in the relevant literature that after 2040 most vehicle sales will be electric and capable of autonomous driving, with connectivity being an essential prerequisite for autonomous driving and potential force for shared ownership (Leech et al., 2015; Kaas et al., 2016; Ranft et al., 2016).

In this paper, we focus on the public finance implications of ACES. The relationship between ACES and public finance is recommended as a subject for further study by the European Commission Joint Research Center (Alonso Raposo et al., 2018, p.151). The topic is briefly discussed in a handful of policy papers (Clark et al., 2017; Peterson and Lewis, 2017; Mares et al., 2018) as well as newspaper articles (e.g. Fung, 2016), but to our knowledge has not received attention in academia. The topic is timely and important, as the technological developments enabling the introduction of ACES progress quickly albeit incrementally, and policy makers need to be prepared for the potential challenges resulting from the impacts of ACES on public finance. This is particularly true due to the path dependencies and potential lock-in effects in suboptimal fiscal regimes which have many precedents in the transport sector.

This article connects the topics of ACES and public finances by combining interdisciplinary research from public finance, transport economics, urban economics, innovation and technology, energy as well as environmental economics. The paper outlines the relevant aspects of public finances of vehicles for a set of countries. We then proceed to summarize the forecasted technological and mobility ramifications of ACES that are important to public revenues and expenditures. This allows us to hypothesize crucial elements in the upcoming of ACES for public finances, as well as make some overarching policy recommendations and propose avenues for further research.

Currently, fuel and vehicle taxation generate approximately 5–12% of federal and up to 30% of local tax revenue in OECD countries (Eurostat, 2018; OECD tax database). On the expenditure side, about 1–3% of national and up to 50% of regional budgets are assigned to land-based transport. The pending introduction of ACES is expected to have significant impacts, among others, on fuel consumption, travel demand, car ownership structure, public transport, infrastructure requirements, and the wider economy, and as a consequence also on fiscal revenues and expenditures. With an increasing electrification of the car fleet, revenues from fuel taxes will fall substantially (and tax rates on electricity are only a fraction of the former). If car- and ride-sharing are adopted widely, revenues from vehicle registration and circulation taxes may decline. Required investments in infrastructure (e.g. telecommunication and energy) and public transport may increase at least in the short and medium run but are likely to decrease in the long run. The impacts of ACES on the wider economy are expected to be positive, but the size of the impact and its fiscal ramifications are highly uncertain. According to Karpilow and Winston (2016), if vehicle automation reduces congestion the US could gain from an increase in employment, an increase in wages and an increase in GDP growth by 1.8% with respect to 2010 GDP levels. For the EU, Ranft et al. (2016) find that when taking into account broader cost savings and productivity effects from vehicle automation as well as potential supportive policies, a GDP increase of up to 7% with respect to 2016 levels might materialize. We argue that tailored public finance policies are essential to ensure that the benefits of ACES outweigh the corresponding costs and thereby help decrease uncertainty in this transition. If the transition towards ACES is not managed well at the policy level using an anticipatory approach, a loss of revenue from vehicle taxation and an increase in negative external costs can impact public finance and social welfare adversely. More specifically, we argue that the increased demand for mobility due to the availability of affordable and convenient ACES and the expected obsolescence of the currently common steering instruments in transport (fuel tax, parking charges) renders the introduction of targeted taxes in line with 'user pays' and 'polluter pays' principles necessary and feasible. We anticipate a shift in the importance of levels of governance: with targeted taxation schemes and declining federal tax revenues from fuel, registration and circulation taxes, local (in particular, urban) levels of governance are likely to gain a higher relevance in transport policy making. Moreover, we emphasize that path dependencies may lead to

suboptimal taxation systems that are hard to re-adjust in the future, mainly due to a lack of public acceptance.

While the focus of this article lies on ACES employed for passenger transport with a capacity that can range from one-person-vehicles to vehicles that hold about a dozen persons (minibuses), many arguments can also be transferred to the freight sector and high-capacity passenger transport vehicles (such as trains, buses, and trams). Moreover, our main arguments also hold for vehicles that rely on other zero-emission technologies, powered for instance by hydrogen.

The paper is structured as follows. Section 2 provides an overview of current transport-related tax revenues and expenditures. Section 3 first gives an outlook on ACES, and proceeds with discussing likely fiscal effects of ACES, and the effect of ACES on transport-related externalities. Section 4 discusses our main hypotheses regarding public finance with respect to ACES and provides recommendations for future research. Finally, Section 5 concludes and makes concrete policy recommendations.

2. Status-quo: Vehicle-related tax revenues and expenditures

This section discusses the status-quo of transport-related taxes and expenditures of selected OECD countries. The aim is to give an overview of vehicle-related public finance for the EU and the US citing official tax revenue and expenditure statistics, in order to provide a frame for the discussion of the potential fiscal implications of ACES. Despite efforts to make fiscal accounts related to vehicles comparable between countries, there is only limited, up-to-date data available (Nash, 2003; Gomez and Vassallo, 2013; Link and Kunert, 2017).

2.1. Revenues from vehicle-related taxes, fees and charges

We can observe substantial differences with respect to vehicle taxation across countries; in terms of available tax instruments, their design and intended goals, and the level of governance at which specific tax revenues are collected. There are however some similarities across countries, especially with regards to the following three tax categories, which make up a large share of vehicle-related tax revenues in most countries, and that are usually levied at the federal level:

Gasoline taxes, including value-added-tax (VAT) and sales tax: Gasoline taxes exist in all OECD countries with the exception of Mexico, which only imposes a VAT.[2] In the United States, all states levy an additional sales tax on gasoline purchases (Pomerleau, 2015; API, 2019). Often tax rates applied to gas and diesel differ: in the EU, there is a tendency to base fuel taxation on the energy content of the fuel source and the contribution to CO_2 pollution, whereas in the US,[3] fuel taxes are intended to internalize road deterioration, and are hence referred to as "road use" taxes. Revenues from gasoline taxes are earmarked in some but not all European countries (European Commission, 2002) for transport purposes.[4]

The **registration taxes** are usually a one-off tax that must be paid when a car, motorcycle or light goods vehicle is registered for the first time in a specific country. In some countries it also has to be levied on purchases of used cars. Usually the registration fee varies between car types and depends for instance on the purchase price, CO_2 emissions/fuel efficiency, cylinder capacity, engine power, vehicle type, weight, fuel, traffic safety (e.g., Denmark), seats (e.g., Italy), vehicle length (e.g., Malta), and vehicle age. In some

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[2] OECD Tax database; http://www.oecd.org/tax/tax-policy/tax-database.htm#VATTables, Table 4.A, 4.6 and Table 4.A4.7.

[3] In the US, States levy taxes on fuel in different ways. For example, some states impose per-gallon excise taxes at the pump, others levy taxes applying to the purchase of gasoline. The average rates vary widely between states (API, 2019). Most states (except for Florida, Maryland and New Hampshire) do not adjust their gasoline tax based on inflation, which means that over time, inflation reduces the purchasing power of the tax rate. In all states, transportation tax revenues need to be supplemented with income and sales tax to pay for transportation infrastructure (The Tax Foundation, 2018).

[4] There are, however, some cases of partial earmarking of fuel tax revenues. This has been necessary in some countries, for instance as a justification for significant increases in fuel taxes, or as an easily recognisable instrument for stable financing of chronic-deficit public services like urban public transport.

countries, electric vehicles are exempt from the registration tax (ACEA, 2017). In most countries, the registration tax is levied at the level of the national government, however, there are exceptions, such as France, Belgium, or the US. In the latter, they may even be city- or county-specific. In general, a value added tax (VAT) or sales tax is levied on top of the purchase price.

The **circulation (or vehicle ownership) tax** is levied on cars registered for usage. It exists in most OECD countries; exceptions within the EU are Estonia, Lithuania, Poland, which do not levy any circulation tax. Its size and computation vary widely across countries. It often depends on factors such as engine power, cylinder capacity, CO2 emissions, fuel consumption, weight, or vehicle age. Similar to the registration tax, it is usually levied by the federal state, but in some countries, it is levied at lower governmental levels. For instance, in Belgium and Russia, it is in the responsibility of the regions. In several countries (e.g. the Netherlands), EVs are exempt from annual circulation taxes (ACEA, 2017).

Other relevant taxes and charges include road tolls, parking charges, taxes on company cars, insurance taxes, costs for periodical inspection (e.g. Belgium), traffic fines, local motoring taxes, and taxes for oil storage (Naess-Schmidt and Winiarczyk, 2009). The corresponding revenues are often earmarked which makes it easier for citizens to compare benefits and payments. Various studies (e.g. from Stockholm, London) show that acceptability of road pricing (and transport-related taxes in general) is higher if earmarked for transport system improvements (e.g. Oberholzer-Gee and Weck-Hannemann, 2002; Schuitema and Steg, 2008).

Vehicle-related taxes contribute a substantial share to fiscal revenues in all OECD countries. There is a noteworthy amount of cross-country heterogeneity in the types of taxes and the respective contribution of each tax to the budget (European Commission, 2002). See Fig. 1 for a selected sample of European countries. Vehicle-related taxes are an important part in all national budgets as they exceed 5% of overall fiscal revenues and can sometimes be as high as 10% (for instance, in the case of Portugal). As mentioned previously, the VAT on vehicle and vehicle part sales together with taxes on fuels and lubricants constitute the lion's share, amounting to over 60–80% of vehicle-related fiscal revenues. The remainder are a varying set of smaller contributions from annual ownership taxes and road tolls (as in the in case of Austria). Fig. 1 shows that across countries, vehicle-related tax revenues mostly vary in their composition, while for a

given country, both the tax composition and the relative contribution of vehicle-related taxes to overall fiscal revenues are fairly stable. As in Europe, also in the US, the primary source of fiscal revenues of vehicles are, fuel taxes collected at the federal and state level. These are usually earmarked for transport-related expenditures (Gomez and Vassallo, 2013).

Vehicle-related fiscal revenues in Europe are levied predominantly at the national level. In Switzerland for example, 60% of revenues are collected at the national level, 35% at the state (i.e. Kanton) level, and 5% at the municipal level (mainly from parking). Vehicle related local sales taxes, also referred to as excise tax are a major revenue component for local governments, especially in the United States. For example, for the municipalities in the Commonwealth of Massachusetts, 73% of vehicle related revenues are in the form of excise taxes (between 25% and 97%), with Boston at 41%. For these municipalities, vehicle-related revenues amount to between 1.5% and 8% of municipal budgets, with Boston (4%) being close to the average of 3.7% (Mares et al., 2018). In the Netherlands, on average 10% of municipal income is from parking fees and up to 27% in cities like Amsterdam (Statline, 2018; CBS, 2014). It is a general phenomenon that the positive net revenue at the federal level is used to counterbalance the substantial shortcoming at the municipal level (BFS, 2017). The share of municipal vehicle revenues in total vehicle revenues varies substantially in the OECD, from 2.8% in Denmark to 29.7% in New Zealand and with an average of 7.3% municipal revenue from transport taxes in the OECD.

Transport-related taxes and charges often serve multiple purposes, which can be assigned to two main categories: revenue generation and steering motives. In most countries, tax revenues generated by vehicle-related taxes enter the general budget; in some countries (such as the United States) taxes are partially earmarked for transport purposes. The revenue generation motive is also underlined by the relative share of vehicle-related fiscal revenues in overall fiscal revenues being rather constant over time for a given country (see Fig. 1). In general, the role of tax instruments has changed over time, also for transport taxes. Historically the main objective of vehicle-related taxes was for general revenue generation but gradually the (environmental) steering effect has gained more prominence, especially in the EU (Kageson, 2005; Vanrykel et al., 2018).

Steering motives are present when taxes are designed such that they lead to a reduction of or compensation for negative externalities generated
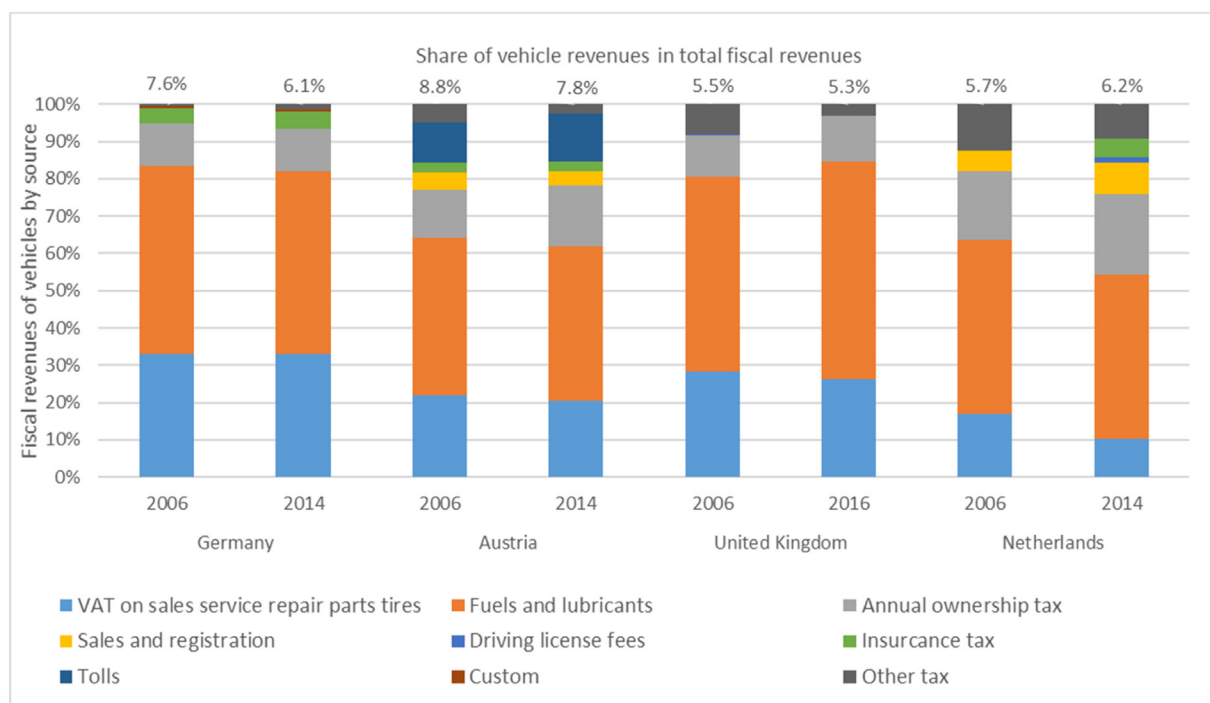

Fig. 1. Fiscal revenues from vehicles.
(Data sources: ACEA (2015, 2017) and Eurostat (2018).)

by transport, with the primary externalities being congestion, accidents, environmental pollution, and the use of public space. Fuel taxes increase in the per/km consumption of a car and the distance driven, and hence affect the demand for vehicle kilometers driven as well as the car type (e.g., Brons et al., 2008). As registration and circulation taxes are often designed such that these encourage the purchase and use of more "environmentally friendly" cars, one can argue that these taxes also have a steering effect in terms of reducing (environmental) externalities.

Tax instruments have important welfare implications. Three main indicators are commonly used to assess the optimality of revenue generation: efficiency of the tax instrument, the governmental level at which the tax is collected, as well as redistribution and the counterbalancing of other market distortions.

The efficiency of the tax instrument is partially determined by the steering motive. Fuel taxes, for example, can be a suitable instrument to affect fuel efficiency and CO_2 emissions (Innes, 1996; Anton-Sarabia and Hernandez-Trillo 2014; Michielsen et al., 2015). Under certain assumptions, efficient prices correspond to the marginal social cost at the efficient level of traffic (Proost et al., 2002). When accounting for the marginal social cost of vehicles, the taxes on fuel are twice the optimal level in the United Kingdom but only half the optimal level in the US (Parry and Small, 2005).[5] Urban and peak vehicle travel is currently underpriced which leads to deadweight losses from severe (i.e. hyper-) congestion (Duranton and Turner, 2011; Anderson, 2014; Adler and Van Ommeren, 2016; Adler et al., 2019). Nonetheless, vehicle tax policies can have unintentional consequences beyond the intended (direct) consequences. For example, a change in registration tax might simultaneously affect nominal circulation tax levels, demand for vehicle ownership, and vehicle kilometers traveled per vehicle (INFRAS, 2002).

Vehicle-related taxes may also have distributional impacts. Current fuel taxes count as regressive (i.e. being a relatively larger burden on low income groups), but some studies suggest that fuel taxes may actually be proportional (see for a discussion, Sterner, 2012). At the local level, transport-related taxes and charges are often in line with user/polluter-pays-principle (e.g. parking charges, traffic fines). Taxes that adhere to the user/polluter-pays-principle result in more efficient market outcomes in the absence of other market distortions (Pigou, 1920; Small and Verhoef, 2007). Even if user fees at the local level of governance (i.e. tolls and parking fees) are potentially regressive and henceforth sometimes criticized for equity reasons, redistribution should generally be tackled at the national level (Ahmad, and Brosio, G. (Eds)., 2015). Overall, taxes should recognize the notion of fairness, differentiation and harmonization as public finance is normative (Tresch, 2014).

2.2. Expenditures

Vehicle-related government expenditures of OECD countries range between 0.5% to 2% of GDP and 1.5% to 5% of overall government budget (i.e. fiscal expenditures). The list of expenditures towards land-based transport is broad and there are substantial differences in the spending allocation between countries. It is challenging to find comparable data, as they accrue at different governmental levels, depending on regulations. Therefore, as an example case, we use the Netherlands for which good data exists and point out where statements can be generalized.

In 2017, the Netherlands spent 2.9% (€8.9 billion) of public budget on land-based transport, see Fig. 2. Construction and maintenance of highways and national roads constitute the lion's share and usually account for >50% of expenditures, exceeding the size of other public infrastructure spending, such as aviation, water, rail and energy. In the Netherlands, highway expenditures make up 56% of fiscal expenditures on land-based transport.

Another 18% are spent on railways and on traffic rule enforcement. By comparison, in the US, 4.8% ($160 billion) of total fiscal revenues are spent on the highway system, with 28% contributed by the federal level and 72% by state and local governments (Musick and Petz, 2015).

Regional governments contribute 12% of public finance towards road construction and maintenance in the Netherlands. This might seem relatively small, however, these 12% constitutes one-fifth (19%) of the overall regional budget. Together with public transport, almost half (42%) of regional finances are spent on transport (CBS, 2017).[6] Subsidies to public transport are usually around 40% of operating costs in Western countries where the main economic reason for subsidizing public transport is a reduction of car externalities (Parry and Small, 2009; Anderson, 2014; Adler and Van Ommeren, 2016). We find a similar picture for Germany where 50% of transport expenditures are attributed to roads, 23% for rail, 10% on local public transport paid 60% on the national level, 27% by cities and 10% by regions (Link and Kunert, 2017).

Another cost to the government, which is typically not mentioned in statistics as the ones presented in Fig. 2, as it only accrues indirectly, are subsidies to electric vehicle sales in the form of tax exemptions, tax credits and additional advantages such as waivers of parking fees, charges and tolls.

2.3. Summary

In summary, a substantial share of government expenditures and revenues is transport related. On average, fuel taxes and transport-related VAT contributions make up 70% of vehicle-related taxes. Typically, fiscal revenues at the local level, such as from parking, are relatively low in absolute terms, but often constitute a substantial share of revenues for local governments (up to 30%). Expenditures on road-based transport make up a substantial share in the fiscal budgets of national governments (typically, about 1–3%) and regional governments (typically, about 3–30%).

There are similarities in the percentage of public revenues and expenditures associated with road transport between countries, but the governmental level at which revenues are collected, as well as the type and justification for the taxes differ substantially across countries. In countries such as the US, expenditures at the national and state levels are similar in size. In many European countries such as Germany and the Netherlands, spending at the national level is much greater that at the local level. Transport related fiscal expenditures amount to a large share of overall regional budgets. They also take up a large share of expenditures at the supra-national level: almost 9.4% of the EU budget is spent on transport through earmarked cohesion funds.[7]

When comparing the level of revenues with expenditures, Gomez and Vassallo (2013) find that EU countries generate enough revenues from transport to subsidize other non-transport-related expenditures, whereas in the US the public sector subsidizes transport-related expenditures. The US road transport system has been in a funding crisis for the past two decades and has a continuous shortfall of about $126 billion per year (Oh and Sinha, 2010; Congressional Budget Office, 2012). One reason is that federal fuel taxes have not been inflation adjusted since 1993 and that capital spending is lower than the required $126 billion/year to maintain the federal highway system's performance (Morris, 2006; Congressional Budget Office, 2012). The US earmarks approximately 50% of fiscal revenues from vehicles for road expenditures but for the EU it is only around 10% (Gomez and Vassallo, 2013).[8]

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[5] With there are restrictions on the implementation of usage-dependent taxes, taxes on the purchase of vehicles are desirable (Fullerton and West, 2002, 2010; De Borger, 2001). Efficient pricing needs to consider capacity restrictions of the road network and the resulting congestion. See Bjertnæs (2017) for a recent example considering the efficient combination of taxes on fuel and vehicles.

[6] Regional governments can use revenues from transport such as parking fees for extra spending on mobility. Local governments do not receive funding for mobility in the Netherlands. 4% of the national budget for mobility is from the EU.

[7] For the 2007 to, 2014 period, the EU earmarked 10 billion per year in cohesion funds directed at road infrastructure and €20.35 billion in Transport European Network program (TEN-T) (Transport and Environment, 2011).

[8] Even so earmarking is uncommon in the EU, expenditures decisions often take revenues into account (INFRAS, 2002).
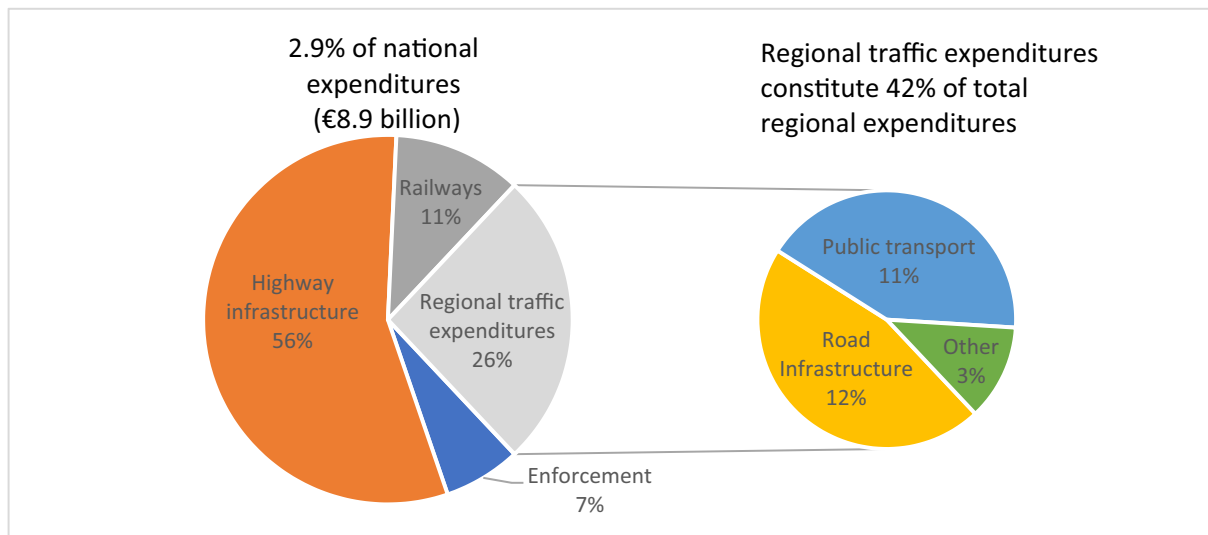
Fig. 2. Fiscal expenditures on ground based transport in the Netherlands.
(Data sources: Wijnen and Stroeker, 2009 and Ministry of Infrastructure, Public Works and Water Management, 2014.)

3. ACES

3.1. Factors affecting adoption and future outlook

This section describes the characteristics of ACES and discusses the expected timeframe of their introduction. The timeframe is a subject debated by the industry (e.g. Waymo, Tesla) as well as by public and private research institutes (Silberg et al., 2012; Saffo and Bergbaum, 2013; KiM, 2015; Kaas et al., 2016; Ranft et al., 2016; Bloomberg, 2017).[9] ACES technologies (i.e. automation, connectivity, electrification, and shared ownership) are highly interdependent, but have emerged at different times and are often discussed independently. In this section, we discuss these technologies in turn and motivate why these are separately, but even more so jointly relevant to public finance.

Autonomous vehicles are a broad category for vehicles that have the capacity to drive without human input (and hence are often referred to as driverless or self-driving vehicles). There is a continuous spectrum of vehicle autonomy. For this paper's purpose, we regard vehicles as autonomous when these can operate longer distances without the assistance of a driver (broadly in-line with Level 3 classification and above, see SAE International, 2016). Autonomous vehicles at level 3 are mostly self-driving, however, might require a driver intervention in specific situations, implying that a designated driver is required at all times. They are currently road tested and expected to become commercially available before 2020. Autonomous ride-sharing depends on full-automation (level 4 and above) which enables driverless mobility and is forecasted to be available on the market starting in the 2020s (Navigant Research, 2016). There is a wide consensus that autonomous vehicle diffusion is imminent, and that diffusion will take the form of a Sigmoid curve, where initial adaptation is slow but followed by years of rapid adaptation, and that by 2040 the majority of vehicles in the Western world will have the capability to drive autonomously (Rogers, 1995; Leech et al., 2015; Kaas. et al., 2016; Ranft et al., 2016).

For this paper's purpose, we regard vehicles as autonomous when these can operate longer distances without the assistance of a driver (broadly in-line with Level 3 classification and above, see SAE International, 2016). Autonomous vehicles at level 3 while in the optimal case do not require driver intervention, still allow for driver intervention in emergency situations

hence a designated driver is required at all times. Level 3 vehicles are currently road tested and are expected to become commercially available before 2020.

Despite a slow start, the diffusion of electric and hybrid vehicles has rapidly increased in the last few years. Globally, the total number of electric cars was >5.1 million in 2018, an increase of 2 million since 2017 (IEA, 2019). China remains the world's largest market, with nearly 1.1 million cars sold in 2018. With 1.2 million electric cars, Europe remained the second largest electric car market, followed by the US with 1.1 million (IEA, 2019).[10] In Europe, Norway remains the leader in terms of market share, with 46% of new electric car sales in 2018, followed by Iceland with 16% and Sweden at 8%. National policies have a major influence on diffusion and ambitions of policy makers and the industry are high, not least due to the goals set in the Paris Climate Agreement. For instance, since 2019 Volvo only produces hybrid and fully electric cars as a commitment to an electric car future.[11] The German Federal Council (Bundesrat) declared the intention to permit only emission-free vehicles from 2030 onwards EU-wide.[12] Britain, France and China have set similar targets for the electrification of vehicles in line with the Paris Climate Agreement. Results concerning stimulating effects on electric and hybrid vehicle sales are mixed, with sales in Europe averaging 1.5%, the US 5% and Japan 20% of new vehicles (Zhou et al., 2015). For instance, the Dutch government exempted plug-in hybrids from registration and circulation tax for a 3-year period, provided scrapping bonuses for high pollution vehicles, and waved charging and parking fees. This stimulus was accompanied by a 5% increase in electric vehicle sales in 2013 at a cost of €500 million, which is 0.18% of fiscal expenditures and 5% of transport expenditures (RVO, 2013; Volkskrant, 2014). Other important factors favorable to electric vehicle diffusion include the substantial cost reductions for batteries (and accompanying regulations), improvements in chargers (such as high-power chargers up to 600 kW and interests in mega-chargers of 1 MW), and the redesigning of vehicle manufacturing platforms to use simpler design architecture which take advantage of much fewer parts in EVs than ICE vehicles (IEA, 2019). By 2025, batteries are expected to be based on cathode chemistries less dependent on cobalt, increasing their energy density and lowering energy costs by a factor of 10 within the next 10 years (The Economist, 2017). Taken together, lower battery costs and innovative

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[9] Earlier studies assumed later introduction dates than more recent studies as technological and regulation barriers were overcome faster than expected. Newer, Anglo-Saxon studies also point to a much more rapid adaptation and earlier market saturation with most studies expecting western countries' car fleets to be almost entirely autonomous by the year 2050.

[10] https://www.iea.org/publications/reports/globalevoutlook2019/
[11] https://www.media.volvocars.com/global/en-gb/media/pressreleases/210058/volvo-cars-to-go-all-electric
[12] https://www.bundesrat.de/DE/plenum/plenum-kompakt/16/948/070.html?view=main%5BDrucken%5D

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design architectures in production are predicted to help achieve cost parity between EV and ICE vehicles by 2025 (McKinsey and Company, 2019). By mid-century, 90% of vehicle sales are expected to be electric (Morgan Stanley, 2017). Autonomous cars are likely to be electric. A main reason is that electric cars are (so far) more expensive in their production, but the operating costs per km are comparably lower. Electric cars will thus be especially favorable for users or groups of users with high mileage, such as it is likely to be the case with autonomous cars in fleet ownership. Conversely, electric cars may benefit from automation, especially if they are capable of accessing charging stations and completing the charging without need for human assistance.

The concept of shared-ownership of vehicles comprises a number of related services such as ride-hailing (e.g. Lyft, Mytaxi), ride-sharing (incl. carpooling, e.g. BlaBla car), shared ownership (Car2go, Greenwheels) and Mobility-as-a-Service (MaaS).[13] These sharing concepts are highly compatible with autonomous electric driving and are likely to become more common once autonomous cars are on the market. In line with an increase in shared transportation, private ownership of cars is likely to decline for the following two reasons. First, autonomous cars will be more expensive than traditional cars (due to the additionally required equipment such as high-quality sensors), and hence ownership only pays off with high mileage. Conversely, shared ownership of autonomous vehicles is expected to yield cost savings to users who travel <10,000 km/year which is almost half of all car travelers in Europe (Odyssee-Mure, 2015; Litman, 2017). Second, a critical mass of users for shared vehicles will probably be easy to reach, due to the expected convenience and affordability (the operating costs of shared services are expected to be low, especially if no driver is needed any longer). The resulting Mohring effect (Mohring, 1972) will lead to reductions in waiting time. All these reasons point towards ACES being to a large extent in shared (fleet) ownership. Not only car-sharing, but also ride-sharing is likely to become more common with the introduction of ACES: coordination among vehicles will become much easier (even route adjustments during the drive can be made easily by an underlying algorithm), and the fact that travel time can be used more productively renders detours for pick-ups and drop-offs less costly. Hence, once transport in shared autonomous vehicles is more affordable than in private vehicles, price-sensitive users, in particular in cities can be expected to switch to the former.

In a stated preference study concerning the willingness to pay for shared and connected autonomous vehicles in Austin (Texas), 41% of respondents were willing to use shared autonomous cars at least once a week and an additional 15% as their regular transport option under the assumption of cost parity with regular vehicles (Bansal et al., 2016). Another study by Cornet et al. (2012) found that a third of urban Germans are predicted to be car-sharing users by 2022 and that attitudes are gradually changing with 87% of respondents aware of the sharing concept and 31.5% of respondents stating that they have gathered further information on car-sharing. Car-sharing has seen double digit annual growth in profitability since 2005 (Cornet et al., 2012). Currently, 50% of global car-sharing users are in the EU, with an annual compound growth rate of around 20% in users projected to reach 16 million users in 2020 (Schiller et al., 2017). Potentially, by 2030, every tenth vehicle sold is shared through some sort of car-sharing scheme (Kaas et al., 2016).

By 2030, ride-sharing is expected to increase substantially, possibly replacing two-thirds of the current taxi market (Burgstaller et al., 2017). Their forecast predicts that 4% of inner city trips will be conducted via ride-hailing services in 2030 relying on one in fourteen cars produced (7% of total car production vs. 3% currently).[14] However, it can be assumed that shared, autonomous transport will be accessible to 70% of population living in urban centers by 2035 (Walker and Johnson, 2016). Chen et al. (2016) expect that each shared autonomous electric vehicle can replace 3.7–6.8
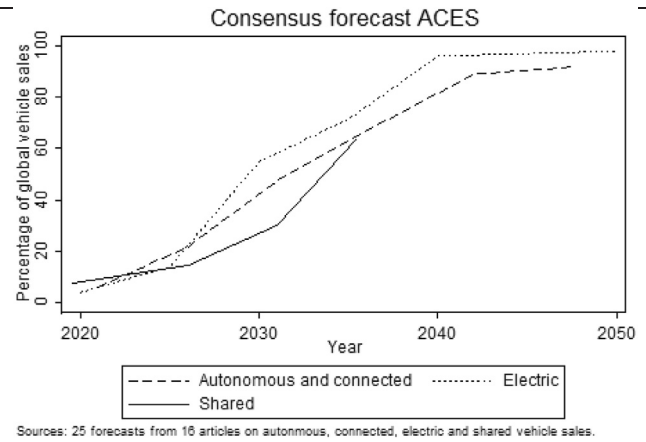
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[13] We define MaaS as an integration of transport services that provides multi-modal mobility without the necessity for private ownership of the transport mode(s).

[14] Private car penetration in cities would decline from 31% in 2015 to 27% in 2030. Ride-hailing cars account for 2% of the overall fleet by 2030, vs. 0.3% today (Burgstaller et al., 2017).

Fig. 3. Consensus forecast ACES diffusion.
(Sources: Underwood (2014); Ihs markit (2014); Leech et al. (2015); KiM (2015) Frost and Sullivan (2016); Kaas et al. (2016); McKerracher et al. (2016); Ranft et al. (2016); Walker and Johnson (2016); Schiller et al. (2017); Schmidt et al. (2018); Litman (2017); Bloomberg (2017); ING (2017); Morgan Stanley Research (2017); Currie (2018).)

privately owned vehicles but that cost competitiveness crucially hinges on recharging automation. Another study projects that MaaS will account for 40% in 2035 and reach around 80% in the decade between 2040 and 2050 (Schmidt et al., 2018). Car- and ride-sharing are predicted to be predominantly attractive in urban settings due to price advantages from economies of scale. Waiting times for ACES are expected to be substantially longer in less densely populated areas (e.g., Bischoff and Maciejewski, 2016).

Connectivity and digitalization are a pre-requisite for efficient car- and ride-sharing. For the actual operation of ACES, the case is less clear. For instance, Alphabet, the parent company of Google and Waymo, intends to keep ACES not continuously connected to the internet to prevent security threats whereas companies such as Audi and BMW plan cars that communicate with each other and with the infrastructure (Condliffe, 2017). Connectivity certainly plays a large role in reducing traffic externalities and in making congestion more predictable (Hensher, 2018).

To illustrate the above discussed trends, we combine 16 studies including 25 forecasts for vehicle automation, electrification and sharing in the developed world to a consensus forecast, shown in Fig. 3. For simplicity and tractability, we assume an equal probability for all forecasts that predict vehicle automation at and above level SAE 3 automation. Although individual forecasts vary greatly, the consensus forecast exhibits similar growth rates of the three technologies. Automation, connectivity and electrification take off somewhat earlier, grow faster and reach an almost complete saturation level by 2040, whereas vehicle sharing is predicted to reach 60% of new vehicle sales by 2035. Unsurprisingly, more recent forecasts have an information advantage over older publications, and the consensus forecast only approximately follows an (s-shaped) sigmoid transition path usually associated with diffusion of innovations, which is not at least due to the aggregation of the underlying forecasts. Also, not all forecasts include predictions until 2050, so after 2040 fewer forecasts are used and almost none of the studies concerning sharing include predictions past 2030. An important takeaway from Fig. 3, is that ACES diffusion happens gradually, implying that ACES are expected to operate in systems with a substantial share of conventional non-ACES vehicles for multiple decades.

As ACES are (initially) more expensive than cars with combustion engines, it is expected that ACES will penetrate the transport service sector as well as the luxury private car market first. The expected higher price of ACES compared to conventional cars suggests that metropolitan areas might see a faster diffusion of ACES than rural areas, due to the higher potential for shared ownership in urban areas (McKerracher et al., 2016). On the other hand, rural areas might be the first to benefit from ACES technology due to the higher technology requirements that come with urban mixed traffic compared to rural roads and highways, which might slow down

ACES diffusion in urban areas (Pernestål Brenden and Kristoffersson, 2018). Regarding electric cars, subsidies and tax exemptions have led to increases in electric vehicle sales in recent years (for instance in the Netherlands, Austria, and Norway), in particular for luxury car models used for business purposes. In the freight sector, electric vehicles are especially sought after for inner city deliveries where regulations on pollution are likely to become stricter.

3.2. Fiscal aspects of ACES

We discuss the expected fiscal effects of ACES by summarizing the findings of existing studies on the direct and indirect effects of ACES under the assumption that current (transport and fiscal) policies remain in place. While the effects cannot be predicted precisely due to the inherent uncertainties associated with technological innovation, their direction can be anticipated. ACES have numerous fiscal implications, which are highly interdependent comparable to transmission through 'ripple effects' (Milakis et al., 2017b).

3.3. Decrease in fuel tax revenues and increase in electricity tax revenues

ACES are expected to lead to a substantial decrease in tax revenues from combustion fuels (as well as VAT and/or sales taxes levied on top of the fuel price and the associated fuel tax), due to electrification of vehicles and efficiency increases. In the US and the Netherlands, even low levels of hybrid and electric vehicle use have already reduced fuel tax revenues sufficiently to alarm governments (Alan, 2018; Rtl Nieuws, 2019). By 2030, new car sales are expected to be close to 100% electric in Europe and the US, and up to 50% globally (McKerracher et al., 2016). Under these assumptions, demand for vehicle fuels is expected to decline by as much as 75% between 2015 and 2030 (McKerracher et al., 2016).

In parallel, electricity demand will go up. By 2030, electric vehicles are expected to account for 3% of global electricity demand (McKerracher et al., 2016). Annual electricity consumption from EVs is projected to increase from 6TWh in 2016 to 1800TWh by 2040, adding 8% to global electricity demand by 2040 (Bloomberg, 2017).

However, foregone fiscal revenues due to declining fuel tax revenues are unlikely to be counterbalanced by higher tax revenues from electricity taxes: oil products for travel (i.e. combustibles) are currently taxed >10 times higher than oil products for electricity production in the OECD (2013) per ton CO2 emission. Coal, a major input to electricity generation in countries such as the US and Germany has an even lower tax rate per ton CO2 emission than oil used for heating. As a result of electrification, tax revenues from combustibles are thus expected to decline noticeably (Wakeley et al., 2008; NSTIFC, 2009; Pisarski and Wachs, 2012).

At the vehicle level, efficiency gains can possibly also be achieved due to automation (independently from the engine), due to more efficient routing, platooning and start-stop avoidance. An overview study by Brown et al. (2013) suggest efficiency gains from these three factors in the range of 5%, 10% and 15%, respectively. Silberg et al. (2012) find that platooning could reduce highway fuel use by up to 20% solely due to the decreased drag coefficient from drafting (Fagnant and Kockelman, 2015). However, Gawron et al. (2018) argue that the net efficiency gain may actually be much smaller (around 9% in their base case), as the system components enabling autonomous driving (computing power, additional weight, etc.) may lead to an increase in power consumption of 3–20% compared to non-automated vehicles.

At the systems level, changes in energy consumption from vehicle usage, and their effect on revenues from taxes imposed on electricity, are difficult to predict, and closely related to the future demand for ACES-based mobility, the extent of sharing, as well as operational characteristics that determine the extent of idle rides for relocation (location adjustment for demand reasons), recharging and parking purposes.

3.4. Decrease in registration and circulation tax revenues

Currently, even during peak hours, only 12% of US cars are in use (Silberg et al., 2012). In large metropolitan areas, 95% of trips tend to be shareable

(Tachet et al., 2017). For Lisbon, if 10% of the vehicle fleet were ACES, these could supply all transport when public transportation is left in place (Martinez and Christ, 2015). Similar figures apply to Austin (Liu et al., 2017).

Car-sharing and ride-sharing may lead to a decrease in the number of registered vehicles in the Western world, as a smaller vehicle fleet can provide similar or even higher levels of mobility (Fagnant and Kockelman, 2014; Martinez and Christ, 2015; Schonberger and Gutmann, 2013). Global vehicle sales might, however, still increase due to an increase in motorization rate. In the Western World, a decrease in registered vehicles is likely to translate into a decline in registration and circulation tax revenues given that current taxation rules remain in place. The decline in registration tax revenues might be dampened if car utilization and in turn the car turnover rate increase (Burgstaller et al., 2017).

3.5. Public sector - roads, energy, telecommunication and transit

Investments in infrastructure (e.g. telecommunication and energy) and subsidies to public transport may increase with the introduction of ACES, in particular in the short and medium run.

The electrification of the vehicle fleet requires investments into smart electricity grids. EVs are expected to increase global electricity consumption moderately (until 2040 by 8% according to Bloomberg, 2017). However, they will contribute to peak-load profiles, in turn requiring additional storage solutions and efficient grid management at the operator level, as well as policies that encourage off-peak charging to prevent power supply and financial shortfalls (Bloomberg, 2017). Research by Morgan Stanley (2017) predicts that global investments of $2.7 trillion are required to prepare the power grid for 500 million electric vehicles until 2040. Under this calculation, the US and the EU, accounting each for one quarter of the global vehicle fleet would need to invest around $250 billion (1.5% of GDP) annually until 2050. By comparison, revenue gains from electricity provision and taxation of electricity are negligible (see the previous subsection on fuel revenues and a study conducted by OECD, 2013).

ACES might affect the costs of road infrastructure maintenance and construction. A higher number of VKT (due to induced demand) is generally associated with higher costs for road maintenance (Clark et al., 2017). In terms of construction, ACES may require less costly safety features such a road shoulders and traffic signs, as well as lower investments in noise protection measures due to electric engines being quieter than fuel combustion engines (Silberg et al., 2012; Fagnant and Kockelman, 2014). Moreover, ACES are expected to use road capacity more efficiently by lowering the necessary safety distance between vehicles, and thereby improving road capacity, and reducing the need for new road construction. However, making ACES use road space more efficiently may require vehicle communication through connectivity and a high market penetration (>40%) of autonomous vehicles (van Arem et al., 2006). The cost for infrastructure that is necessary for vehicle connectivity, in particular telecommunication technologies, may be high and in constant need of upgrading with advances in technology (Silberg et al., 2012). Therefore, the effect of ACES on public expenditures on road construction and maintenance is fairly unclear for lower penetration rates (Eugensson et al., 2013; Wagner et al., 2014). At considerable ACES market penetration, Silberg et al. (2012) expect a small, but significant decline in infrastructure spending by 10%.[15]

Public transport scenarios for ACES are highly speculative, since ACES and public transport are not exclusive concepts. In the future, ACES could serve an important role in public transport. For example, the problem of how to travel the "last mile" of a journey after a shared long-distance travel could be solved through innovative MaaS concepts (Begg, 2014).[16] Low density and low quality public transport is expected to be replaced by

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[15] Platooning on highways can increase capacity by up to 500% but according to a study by the Boston Consulting group, Amsterdam and similar cities requires substantial road capacity upgrades to allow for autonomous vehicles. http://nltimes.nl/2016/10/11/amsterdam-ready-handle-self-driving-cars-bcg.

[16] Mobility options do not necessarily have to decrease in the absence of public transit. For instance, Innisfil, a 36,000-inhabitant town near Toronto, is relying on Uber to provide last-mile public transit services (May, 2017).

ACES in the long term (Litman, 2017), since losses from a shrinking user base cannot be recovered through higher fares that would accelerate the downward service spiral and increases in already large subsidies. Current subsidies to local transit in Europe are between 40 and 60% of operating cost with even higher relative subsidies in most cities in the US. Also, long-distance rail transit requires large up-front infrastructure investments with large investment horizons (+30 years) that is going to come under pressure from ACES (Silberg et al., 2012).[17]

3.6. Macroeconomic effects and fiscal consequences

ACES can (indirectly) affect revenues from large-base taxes such as the income tax, corporate tax, and capital gains tax, as well public expenditures, for instance for unemployment benefits. Such effects may accrue via the labor market, via the taxation of car manufacturers and fleet operators, or via ACES' impacts on the wider economy (including the freight sector). At this point, however, there remains a high level of uncertainty concerning the macroeconomic effects of ACES, not least because the outcomes depend on public policies.[18]

It is generally expected that there will be an overall positive effect of ACES on productivity and GDP. The forecasted effects are highly speculative and tend to be in a range of an adding 4–12% to GDP in the long run. This is in line with a 0.15% increase in GDP growth rate from autonomous vehicles between 2021 and 2050 for the EU and the US (Shanker et al., 2013; Ranft et al., 2016). Productivity gains depend on mobility gains but also on cost savings (detailed throughout Section 3, see also Shanker et al., 2013). Socio-economic benefits of autonomous vehicles are expected to be around £50 billion (2% of GDP in 2018) per year by 2030 for the United Kingdom (Leech et al., 2015). A recent study by Karpilow and Winston (2016) expects for California an annual boost to the GDP growth rate by 1.8% and an increase in annual labor earnings by more than $100 billion, under the condition that ACES can reduce congestion to a minimum. Note that most studies focusing on macroeconomic effects of automated driving combine freight and passenger transport, also because the macroeconomic effects are hard to disentangle between freight and passenger transport.

ACES may strongly affect the labor market, most evidently by reducing the number of jobs in the transport and logistics sector (Shanker et al., 2013; Davidson and Spinoulas, 2015; Guerra, 2016; Alonso Raposo et al., 2018). To underline the size of this issue, the EU transport sector employs 5% of the workforce and an additional 2% for employment in related sectors of the economy (ACEA, 2018), and truck drivers (and related jobs) are the most common profession in the majority of US states (NPR, 2015). By 2030, ride-sharing is supposed to increase eight-fold and replace two-thirds of current taxi market, rendering potentially 2.6 million drivers globally redundant, according to a study conducted by Burgstaller et al. (2017). Additional jobs that might be replaced include vehicle maintenance staff, employees at driving schools, employees of insurance companies, park and traffic surveillance staff, and even emergency room staff (Hörl et al., 2016).[19] The reduction in employment is expected to predominantly affect low-income jobs. New jobs are expected to be created in the more advanced tech sectors, requiring a different skill set (Alonso Raposo et al., 2018) and potentially leading to a labor market polarization (see Thuemmel, 2018).

At least for a certain period, the automation of labor in the transport sector is predicted to progress faster than new jobs in this sector will be created, in particular in the absence of concrete policy measures. The ITF (2017) proposes the introduction of a licensing system on ACES in freight in order to slow down the introduction of ACES, thereby supporting a labor market transition that avoids major unemployment spills. The labor market outcomes of ACES will also depend on public policy regarding skill upgrading through education (Ranft et al., 2016). The topic relates to the larger discussion on how automatization will affect the labor market and society as a whole (Frey and Osborne, 2017), and which measures should be taken (e.g., basic income, higher taxes on capital).[20]

The negative employment effects may be partially counterbalanced by better matching in the labor market due to a higher acceptance for longer commuting distances and for higher mobility in general.[21] An increase in mobility and therefore an improvement in accessibility has benefited the United States and Europe substantially in the last decades (Duranton et al., 2014; Adler et al., forthcoming).

3.7. Public finance policy in the advent of ACES

3.7.1. Differentiated road tolls

Currently, 1% of GDP is lost in travel time due to congestion each year in the EU-28 (European Commission, 2011; CEBR, 2014). Especially urban centers are affected by congestion. The TomTom traffic index shows that congestion levels in urban areas are deteriorating globally, with larger urban areas experiencing average travel times 66% above free flow levels and up to twice as long for peak hours.[22]

ACES are predicted to have a large effect on the vehicle kilometers traveled (VKT), especially in the medium and long run (Litman, 2015). Trommer et al. (2016) estimate that autonomous vehicles are likely to increase total vehicle travel by 3–9% by 2035, and passenger miles might even increase by 25% (Fagnant and Kockelman, 2014; Martinez and Christ, 2015; McKerracher et al., 2016). For the United States, vehicle kilometers traveled are predicted to grow by 14% from non-drivers alone, which might add 40% of VKT (Brown et al., 2013; Harper et al., 2016). The main reasons behind the expected increase in VKT is induced demand due to more efficient, comfortable, inexpensive and possibly also reliable[23] provision of mobility services, and current steering instruments becoming widely obsolete: taxes on fuel will lose their effect on electric vehicles, with electricity being significantly less taxed than gasoline, and parking charges will not prevent autonomous vehicles from entering areas with land scarcity as they can keep cruising or park elsewhere (Ostermeijer et al., 2018). Also parking charges will become less effective, as automated vehicles can drive to cheaper parking locations or keep cruising (in both cases creating additional VKT). Cheaper car-based mobility might also lead to people switching from transport modes with more efficient space usage (public transport, cycling or walking) to ACES. ACES will also attract new user groups such as the elderly, disabled, and young people, who currently tend to be restricted in engaging in independent mobility. Diffusion of ACES will also lead to additional and longer trips because of increased travel comfort, low costs and the fact that travel time can be used productively. Moreover, idle rides will not only take place in order for ACES to find cheap or even unpriced parking, but also for re-charging purposes, or to optimize vehicle availability according to expected demand patterns (empty ACES have no value of time, i.e. they do not experience disutility from spending time in congested conditions as human drivers do, see for instance Kaddoura and Bischoff, 2017).

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[17] High speed mass transport services, e.g. high-speed rail, might have sufficient comparative advantage to autonomous vehicles rendering complementary to ACES. Local public transit services, however, are likely to be close substitutes to ACES and thus to suffer substantially under ACES competition. This will increase pressure on local public finance that subsidizes these services or alternatively these services are no longer provided.

[18] Bertoncello and Wee (2015), for instance, speculate that ACES bring about changes in spending patterns because of more leisure time from reductions in travel costs and therefore a higher disposable income.

[19] Although the car industry is already highly automated, there are concerns that even more jobs will be lost because EVs are much simpler to assemble than cars with combustion engines (The Economist, 2017).

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[20] Concrete measures targeted more specifically at the introduction of ACES can be found in the "Driving Future Platform" of the EU Parliament: https://connectedautomateddriving.eu/event/4th-driving-future-event

[21] Karpilow and Winston (2016) estimate that a reduction in congestion may lead to an increase in employment by up to 15% in California.

[22] https://www.tomtom.com/en_gb/trafficindex/list?citySize=LARGE&continent=ALL&country=ALL

[23] Hensher (2018) argues that with a high penetration rate of AVs congestion will become more predictable.

An increase in VKT can increase road congestion significantly, especially in urban areas and when market penetration rates of automated vehicles are low (Smith, 2012; Kaddoura and Bischoff, 2017; Adler, 2017; Pernestål Brenden and Kristoffersson, 2018). For instance, Calvert et al. (2017) found that low-level automated vehicles in mixed traffic have a negative effect on traffic flow and road capacity, and that improvements in traffic flow occur at penetration rates above 70%; above 50% autonomous vehicles penetration, gains of around 5–15% in capacity at bottlenecks and 15%–20% without bottlenecks can be expected (see Milakis et al., 2015, 2017a for an overview).[24] While city centers might become denser (also because of the availability of affordable, convenient transport in the form of ACES, see Bischoff and Maciejewski, 2016), ACES might also contribute to a reduction in urban density on the fringes of the city and an increase in urban sprawl, as a reduction in the value of travel time savings might render longer-distance commutes more attractive. Thakur et al. (2016) simulate that suburbs that are further than 30 km from Melbourne's central business district might increase in population by 2–4% due to vehicle automation.

We argue that the likely increase in vehicle kilometers traveled (VKT) (and associated consequences, such as increased urban sprawl) can be countered efficiently by using (differentiated) road tolls (Smith, 2012; Adler, 2017, Adler et al., 2019; Bloomberg Philanthropies, 2017 make similar arguments). Road tolls have been advocated for decades, starting with Vickrey (1969), with the aim of internalizing the externalities resulting from transportation. Due to road tolls being usage-dependent, they are more effective in reducing environmental and congestion externalities than registration and circulation taxes, especially if they are differentiated in time and space (Langer et al., 2017; Vanrykel et al., 2018). Road tolls also tend to be a better instrument for raising revenue than fuel taxes because travel is less elastic than fuel consumption (Parry and Small, 2005). Moreover, there is the possibility of a 'double benefit' and 'virtuous circle' depending on the use of revenue (Small, 2005).

However, road tolls have been successfully introduced in a few cities only (among others, in Singapore, London, Stockholm) and few road stretches (e.g., toll lanes in the US) so far. Most of the existing road toll implementations have high transaction costs, are second- or third-best, and lack public acceptance. The latter is especially true before their introduction (as opposed to after the introduction), when congestion is not considered a sizable problem by citizens, and when the use of the toll revenues is unclear and not earmarked for transport-related purposes (see De Borger and Proost, 2012).

With the advent of ACES, the problems associated with the current tolling schemes are likely to be substantially reduced. Lower transaction costs can be achieved from advancements in software and digitalization (e.g. ubiquitous GPS tracking of ACES and a close to 100% smartphone penetration rate).[25] The same technologies allow for new, more targeted tax instruments with high flexibility that can be designed with the aim of limiting the presence of negative externalities (see Section 3.3), and allowing for a system-wide tax scheme rather than a tax scheme applied to selected road (stretches), which in turn limits spillover effects (i.e., traffic from tolled (main) roads being shifted to untolled (local) roads) (Eliasson, 2014; Calthrop and Proost, 1998; Ostrovsky and Schwarz, 2018). The tolls can, for instance, be set such that they take into account trip length, time of day, vehicle type (or even the occupancy rate) as well as the type of roads used along the trip (see also Hörl et al., 2016). Providers may then offer clients to choose between algorithms that select between cheaper and faster routes (Ostrovsky and Schwarz, 2018).

Also, a higher degree of acceptance of future road pricing schemes with ACES (compared to current and past road pricing schemes), and in turn a

higher political viability seems achievable. A main reason is that with shared ownership, the tolls may be directly charged to the individual traveler (and voter), but to the mobility service providers and/or fleet owners of ACES (Hensher, 2018). Depending on the market structure and demand elasticity these service providers will then impose these costs partially or fully on the consumers. Alternatively, even if road charges are directly charged to the consumer, the toll collection will be very convenient to users, as GPS-tracking of vehicles will avoid the necessity for toll booths. Another argument brought forward by Ostrovsky and Schwarz (2018), is that, unlike in the Vickrey bottleneck model where the individual drivers are equally well off after introducing a time-differentiated road toll (before they encountered the same cost by waiting in the queue), they are better off in a scenario with ride-sharing: without tolls each driver pays the entire cost in terms of waiting time; with tolls and if the ride is shared with at least another person, they pay less than half of the costs associated with the untolled equilibrium. Moreover, citizens can probably be convinced that fuel tax revenues need to be replaced by other tax revenues when fleet electrification proceeds, at least as long as the average cost of travel is still lower than or equal to the costs associated with the pre-ACES era.

Besides steering motives, revenue motives can also be highly relevant for the implementation of tolling schemes, as revenues from other vehicle-related tax bases (fuel, registration, circulation taxes) will decrease (as discussed in Section 3).[26] The potential tax base for road tolls is large, while it is fairly small for registration and circulation taxes (in particular if car- and ride-sharing become more common). Earmarking the toll revenues for transport purposes will be beneficial for acceptance reasons (and can be justified with required infrastructure investments for ACES); however, (at least part of) the road toll revenues might also be transferred to the general budget of the tax levying governance body for financing other public expenses (similarly, to the current use of fuel taxes revenues, in particular in European countries).

Clearly, measures on the supply side (e.g., restricting the number of ACES) are also possible in order to avoid an increase in negative externalities, in particular from increased road congestion. Besides not being optimal from a welfare perspective, it is questionable whether they can be sustained in the long-run, if citizens and fleet providers lobby for better access to ACES. While restrictions in the number of ACES within a specific area do not create fiscal revenues per se, the licenses to operate ACES (at the level of the fleet provider or at the per-car level) could be taxed or auctioned by governmental bodies.

3.7.2. Federal taxes and local primacy

With the advent of ACES, both local as well as national bodies will have a strong incentive to implement road tolls, for revenue as well as steering reasons, as outlined in the previous section. National bodies are likely to be relatively more focused on revenue motives, as vehicle-related tax revenues (most of which are currently collected at the federal level, see Section 2.1) are expected to decrease substantially (as argued in Section 3). An alternative to the decrease in fiscal revenues from vehicle related taxes might come in a form of a distance traveled charged as these do not depend on the fuel type and vehicle ownership.

Federal governments will be tempted to counterbalance the forgone tax revenues due to the introduction of ACES, as macroeconomic benefits from ACES probably only materialize at high penetration rates in the long run (see Section 3.2). As argued in the previous section, the primary and most obvious possibility to generate additional tax revenues are road tolls; more specialized taxes that target ACES directly (e.g. on batteries) may lead to innovation hampering. Higher taxes on electricity are a rather weak alternative as gasoline taxes are currently multiple factors larger than those of electricity (OECD, 2013). Other counterarguments are the expected low public acceptance, and the possibility for tax evasion by private

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[24] Note that there are studies that predict much larger capacity gains such as Pinjari et al. (2013) who estimate that connected AVs will cause a 22% increase in highway capacity at 50% market penetration, 50% capacity increase at 80% market penetration, and 80% increase at 100% market capacity.

[25] "[…] theory of optimal tax systems […] embraces the insights of optimal taxation but also considers the technology of raising taxes and the constraints placed upon tax policy by that technology" (Slemrod, 1989).

[26] A good example is the recently leaked debate in the Dutch Transport ministry concerning the introduction of distance-based charging in order to compensate for the fuel tax revenues due to the higher share of electric (and fuel-efficient) vehicles. Most interestingly, it is being discussed whether the charge should only apply to electric vehicles (RTL Nieuws, 2019).

generation of electricity (e.g., using solar panels). We are unaware of any earmarking of electricity tax revenues towards transport agencies. The comparably low revenue and the insufficient steering potential make additional taxes on electricity used for mobility purposes an unsuitable substitute for fuel taxes (Alan, 2018). Besides road tolls, other feasible alternatives are a moderate raise in tax rates that typically have a large base (income tax, corporate income tax, consumption taxes, etc.), or the introduction of a robot tax on ACES replacing drivers (for further discussion, see Thuemmel, 2018).

It is conceivable that in the future the dominance of federal states in levying vehicle-related taxes will shrink. The main reason is that cities are likely to face negative externalities of ACES (congestion, pollution, noise, accidents) more strongly but also at an earlier point in time, as they are likely to encounter ACES diffusion prior to other areas (Kaas et al., 2016; RCCAO;, 2016). This should make them more inclined to implement steering instruments such as the differentiated road tolls described in the previous section. The same is true for regulatory measures: cities might for instance require ACES fleet operators to tender for or buy licenses for their cars, fulfill specific safety and environmental standards, or have ACES in public ownership.[27] Revenues from road tolls will then be captured by these local (city) governments, as it is the case with most currently existing urban tolling schemes (e.g., Milan, London, and virtually all parking schemes).[28] Moreover, cities will seek a replacement for a decrease in revenues from parking charges and traffic fines.

Substantial inter-jurisdictional competition between local or regional public decision-makers may emerge. National bodies will mostly focus on the taxation of traffic on national roads (mostly highways and other main roads of national interest), while local (in particular urban) governance bodies will focus on the taxation of the secondary road network. As a substantial share of national roads (typically those with much traffic) tend to be located within city boundaries, legal disputes may arise about who is able to determine the level of the road toll, and even more importantly, who is the recipient of tax revenues. Multiple tax systems based on different technologies are usually undesirable due to transaction costs; however, revenue sharing may be an option. Similar issues arise at a supranational level, including freight transport. For instance, regarding registration taxes (and the corresponding VAT and excise taxes) as well as circulation taxes, tax competition, and potentially a race to the bottom in tax rates, may emerge: national governments have an incentive to lower their taxes rates in order for fleet operators to register their car fleet in their country (Clark et al., 2017). In countries where registration taxes are levied at the regional or local level, this competition may take place even within jurisdictional units located in the same country (Vanrykel et al., 2018).

Under the current vehicle taxation system at the federal level, the share of vehicle-related taxes is likely to decrease, and in turn their steering power is likely to diminish with the diffusion of ACES. Cities are then likely to replace national or regional levels as the most relevant segmentation dimension that determines mobility behavior in terms of speed and scope (Kaas et al., 2016). A future with high penetration rates of ACES may thus entail higher vehicle-related tax revenues for local level of governance (in particular cities), and lower vehicle-related tax revenues for higher governance levels (in particular, the federal state). We do not expect such a pronounced shift on the expenditure side. As a result, we expect ACES to further deepen inequalities between cities and rural areas in terms of access to affordable mobility, as well as steering power increasingly being shifted to local (urban) level of governance. This is in no case a forgone conclusion as political, procedural and historical country specifics will be highly relevant in the transition towards the new tax equilibrium.

3.7.3. Timing, path dependencies and lock-in effects

Path-dependencies and lock-in effects in suboptimal equilibria play a substantial role in public finance (Kato, 2003), including the transport sector.[29] Path dependence of decisions acknowledges that a set of decisions is determined by past decisions. Path dependencies can create conditions which lead to inefficient outcomes which may or may not be remediable (Liebowitz and Margolis, 1995). When the transaction cost necessary to reverse past decisions are considered prohibitive, this can lead to a lock-in to an inefficient situation which is near impossible to change (David, 1985). In the context of ACES and public finance implications, path dependencies and lock-in effects might be highly relevant, for instance regarding ownership structures: fleet owners may potentially become very influential and gain market power in many regions (possibly even leading to a deterioration of alternative transport modes) in particular due to the presence of economies of scale. This can (partially) be avoided by establishing regulations that actively encourage competition, which has recently happened in other network- and platform-based industries: energy, telecommunication, insurance, and banking are prime examples, where regulations have been introduced that shall decrease the consumers' switching costs between providers and increase price transparency between providers. Market power of single fleet providers can also be limited by requiring them to participate in public tenders (with specified requirements concerning pricing and service levels). The later such regulations are imposed, the harder it be to combat and regulate market dominance by one or few providers, as evident from other platform-based business models: Google, Facebook, Amazon, Apple, AirBnB, and from the transport sector, most famously, Uber, which used their first mover advantage to set new behavioral norms (Kenney and Zysman, 2016). This is especially true if the regulation (potentially) leads to price increases for consumers, and hence lacks public support.

Another important aspect is that fiscal policies can have an ambiguous effect on innovation. If innovations are taxed too much and too early, their roll-out will be slowed down. If they are not taxed enough or even subsidized, tax advantages might be difficult to abolish when the penetration rate of the new technology has gained a significant market share, due to a lack of public acceptance.

Overall, the transition period towards ACES might be costly in terms of foregone taxes (at least temporarily) and lock-in effects regarding suboptimal subsidies.

3.8. Conclusions and policy implications

Much of the recent mobility literature, frequently motivated by technological aspects (and often under the header of "smart mobility"), is dominated by the view that ACES will predominantly have positive effects: through the conservation of fossil fuels (if electricity for EVs is sourced from renewables), by providing benefits to people who are currently unable to engage in independent mobility, the improved possibility for using travel time productively, an overall increase in transport efficiency, decrease in travel time, and the freeing up of public parking space. In this paper we argue that these positive effects may materialize in the medium to long term if ACES are well-managed in terms of public policy. Conversely, almost none of the benefits might accrue (not even in the long term) if the process is not well managed, due to path-dependencies with suboptimal outcomes in terms of forgone tax revenue and high costs for the public sector. We discuss potential implications of these new technologies on fiscal revenues and expenditures. Given that in most OECD countries a considerable share of (federal) tax revenues is composed of vehicle-related taxes (5–10%), and given the expectation that ACES will require large infrastructure

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[27] In a comparable case, some cities require car-sharing providers to operate (exclusively) electric cars.

[28] The local implementation of tolls is in line with benefit principle, which states that those who use a service should pay for the resulting costs (Lindahl, 1919; Musgrave et al., 1987) as well as in line with a general trend of transferring fiscal responsibility to local governments (see for instance, Goldman and Wachs, 2003).

[29] An illustrative example concerns shipping: a tax exemption for fuel used for inland shipping along the entire Rhine river, has been signed in 1831 (Mannheim Act); to this date the taxation of fuel along the Rhine depends on whether the fuel is used for water or road transport (CCNR, 2018). Another prominent example is the tax rate imposed on diesel, which is lower than the tax imposed on petrol in many European countries, mainly due to lobby efforts by the logistics and the agricultural sector (Transport and Environment, 2015). The resulting larger share of Diesel cars in these countries and their higher PMx emissions compared to petrol-based cars led to substantial air quality problems in urban areas.

investments and may strongly affect public transport provision as well as labor market outcomes, it is likely that both fiscal revenues and expenditures will be substantially affected by the advent of ACES.

Clearly, as it is generally the case with disruptive technologies, future scenarios are surrounded with uncertainty concerning technological developments, uptake by the public, and industry structure. Even though technological development will likely take place at the global level, the uptake and industry structure might be local, and influenced by local preferences, institutional settings and the availability and quality of alternative modes (to mention just a few factors). Despite the inherent uncertainty concerning the future, we argue that policy makers should be aware of upcoming public finance challenges and take them into account in their current and near-term decision making. In the near term, public and academic discussion should focus on developing a firmer grasp on the complex interrelationship between public finance and ACES. For this reason, we mapped out the status quo of the relationships between public finance and (passenger) transport, summarized the likely fiscal implications of ACES under a laissez faire approach, and came up with hypotheses concerning active public finance policy in the advent of ACES. With the advent of ACES, it should be possible to design public finances that account for the external costs of transport through the use of tax instruments enabled by the new technologies. Specifically, we argue that the advent of ACES will require, but at the same time enable (differentiated) road tolling at a wider scale. We also argue that ACES will lead to disruptions in the fiscal revenues and expenditures that accrue to federal and local governments, likely shifting more power in transport policy making to the local (urban) level of governance. Third, we argue that path dependencies are strong in transport policy making, potentially leading to suboptimal fiscal policies that are hard to re-adjust in the future. In line with citizens' preference for "predictable institutions" (Teknologiradet, 2017), fiscal measures should be transparent, predictable and easy to understand (e.g. sudden price shocks should be avoided).

As ACES are a developing and potentially fast spreading technology, dynamic policy adaptation is likely to be required, an area of research that has so far not been very evident in transport economics but has been researched more widely in other areas, such as environmental economics (e.g. Fischer et al., 2003). Before introducing new policy instruments, it is vital to identify risks of lock-in effects, for instance by designing and evaluating different policy transition paths. More specifically, future research should focus on how differentiated road tolls can be designed in an optimal way, taking into account both steering and revenue considerations, as well as the potential negative effect on ACES uptake and innovation, as well as distributional impacts. Effects on related markets (in particular, the labor market and land use), potential long-run dynamics and the influence of factors such as city structure and institutional/legal settings need to be considered as well. Focus should also put on analyzing the interplay between local, regional and federal level of governance in the light of the introduction of ACES and the corresponding effects on fiscal revenues and expenditures at these different levels of governance, possibly using game theory and political economy approaches. Finally, general equilibrium models and input-output analyses will be useful to predict the economic effects of different fiscal policies regarding ACES for different spatial units and socio-economic groups.

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