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Policy Implications of Autonomous Vehicles

CHAPTER SIX

Policy implications of the potential carbon dioxide (CO_2) emission and energy impacts of highly automated vehicles

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Contents

Abstract

This chapter explores the extent to which the adoption of highly automated vehicles (AVs) will lead to carbon dioxide (CO_2) emission reduction in the future. Additionally, policy implications are given. Based on existing literature, this chapter shows that the adoption of AVs will result in a modest improvement of CO_2 emission per kilometer traveled compared to non-autonomous vehicles in the future. Combined with the expectations that AVs will lead to a modest to, even, high growth in vehicle kilometers traveled (VKT) compared to business as usual, the net energy and CO_2 emission balance for AVs seems, at its best, to be neutral, but is probably negative. The potential accelerating role of AVs in relation to the uptake of electric vehicles might have the largest positive impacts on the CO_2 emissions per kilometer driven, but this accelerating role of AV technology in relation to the uptake of electric vehicles is uncertain. For the time being the most useful policy implication to curb road transport CO_2 emissions seems to be to continue with policies that promote the use of alternatives for fossil fuels, such as electricity.

Keywords: Automated vehicles, Environment, Carbon dioxide emission, Policy implications

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1. Introduction

In 2016 the current transport system emitted around 8.05 Gt of carbon dioxide (CO_2) worldwide, or 25% of all economic sectors (industry, buildings, other) (IEA, 2019). Recently, the IPCC (2018) estimated that human activities (for which CO_2 emission is the most important) caused approximately 1.0 °C of global warming above pre-industrial levels. Additionally, they state that global warming is *likely* to reach 1.5 °C between 2030 and 2052 if it continues to increase at the current rate. Road-based travel is responsible for the largest share of the transport CO_2 emissions at 68% (IEA, 2019). Broadly speaking, it is difficult to reduce CO_2 emission caused by transport. For example, within the European Union greenhouse gas emissions from transport (including aviation) increased by 25% between 1990 and 2017, despite efforts to reduce these emissions (EEA, 2019). New technologies such as biofuels, hydrogen and electric vehicles have penetrated the market far slower than optimists in the 1990s expected. As well as this, attaining behavioral change, whereby people would use the more environmentally friendly transport modes (public transport, bicycles, walking) rather than to cars, has turned out to be difficult. Perhaps there is hope on the technological horizon. This chapter aims to analyze whether highly automated vehicles will contribute toward reducing the CO_2 emissions of transport in the future. The questions this chapter aims to answer are: "*to what extent will the adoption of highly automated vehicles lead to CO_2 emission reduction in the future*"? And: "*what policies might be needed to steer the possible adoption of highly automated vehicles in the right direction from an environmental point of view*"?

"Highly automated" vehicles is a rather vague concept. In the scientific papers reviewed for this chapter different definitions of automated vehicles are used (implicitly or explicitly). In this chapter, broadly-based results and analysis from various papers are used which define automated vehicles as a vehicle that can navigate itself and have connectivity capabilities (vehicle-to-vehicle, vehicle-to-infrastructure and other cooperative communication networks) (definition based on Taiebat et al., 2018).

In this chapter, in Section 2, the approach used to write this chapter is given. In Section 3, the mechanisms which might affect AVs' energy use (and CO_2 emissions) per kilometer driven are explained. In Section 4, the potential energy and CO_2 emission impacts per kilometer driven of AVs are explored quantitatively. Section 5, analyses the relation between the adoption developments of AV and battery electric vehicles (BEV). In Section 6, the potential volume impacts of AVs compared to conventional vehicles are shown in order to explore the total future environmental impacts of AVs. In Section 7, the policy implications are discussed.

2. Approach

This paper is based on a review of scientific literature. A four-step approach was followed to select and review literature for this chapter:

1. The first step in the approach was to find scientific literature on the relation between highly automated vehicles and the environment. The search quickly led to two very elaborate papers on this topic. The first is by Taiebat et al. (2018) which contains a literature review of this topic using 111 recent scientific papers. It was decided not to repeat this review but, instead, to use this review paper in this chapter of the book to give state-of-the-art knowledge related to energy use and the CO_2 emission impacts of AVs per kilometer driven. The other elaborate paper found was by Gawron et al. (2018) who carried out a very extensive and high quality Life Cycle Assessment of AVs. Again, it was decided to use this paper in this chapter to show quantitatively what the potential environmental impacts of AVs might be, per kilometer driven.
2. One of the results of the analysis in step 1 was that powertrain developments (toward the uptake of BEVs) are dominant in achieving relatively high CO_2 emission reductions per kilometer driven. Therefore, in step 2, based on a brief scientific literature overview, a concise analysis was made of the interaction between AV development and BEV development. The "scopus.com" and "google scholar" search machines were used, applying the strings: "autonomous vehicles" AND "electric vehicles" (synonyms for "autonomous vehicles" and "electric vehicles" were also used in all kinds of combinations).
3. In the two previous research steps the impacts of AVs on CO_2 emission and energy use per kilometer driven were explored. Naturally, total CO_2 emission and the energy impacts of AVs are the result of the CO_2 emission factor estimates (g/km traveled) multiplied by the estimated kilometers driven (Vehicle Kilometer Traveled, VKT). In order to be able to explore total CO_2 emission and the energy impacts of AVs, in the third research step some very recent literature on VKT estimations for AVs was briefly reviewed. Only very recent papers were selected (at the time of writing this chapter—summer 2019). The studies that were selected

used different research methods, they focused on different regions and they used different assumptions.
4. Finally, based on the results of steps one to three, policy implications (if any) were discussed.

3. Energy use and CO_2 emission per kilometer driven

The CO_2 emission of road transport is the simple result of an emission factor (grams of CO_2 per kilometer driven) multiplied by the amount of kilometers driven. Broadly speaking, there is consensus in the literature studied that highly automated vehicles will decrease CO_2 emissions per kilometer driven. In an extensive literature review by Taiebat et al. (2018), they conclude that it is generally expected that AVs will improve energy efficiency and reduce CO_2 emissions per kilometer driven. Table 1 summarizes their results. They show that in scientific literature, four major mechanisms can be distinguished which affect energy use (and CO_2 emissions) per kilometer driven.

The first mechanism, vehicle operation, is, among other things, related to the notion that AV algorithms can eliminate the heterogeneity in real-time decisions which human drivers make while driving, resulting in an

Table 1 Major influencing mechanisms and their positive and negative impacts on AV fuel efficiency (Taiebat et al., 2018).

Major influencing mechanisms	Positive impacts	Negative impacts
Vehicle operation Vehicle design Electrification Platooning	Higher energy efficiency • Optimal driving cycle • Eco-routing • Reduce cold starts • Less idling • Less speed fluctuations • Powertrain downsizing • Self-parking Safety-enabled vehicle light-weighting Vehicle right-sizing Complementary electrification benefits Platooning	Faster highway speeds Additional ICT equipment needs for navigation and communication Aerodynamic shape alteration Higher auxiliary power requirement

optimized driving cycle. AVs may drive less dynamically (aggressively) compared to human driven vehicles, with less speed fluctuations, with fewer complete stops, with less idling, and so forth. All of the examples given result in lower energy consumption per kilometer driven compared to a human driver. On the other hand, AVs might be safer in operation due to the elimination of human errors that may result when higher speeds are allowed, and which counteracts the efficiency gains just mentioned.

The second mechanism, vehicle design, is a bit more uncertain but here, the general notion is that the safety of AVs might be higher compared to conventional vehicles, resulting in opportunities to design relatively light and small AV vehicles (and thus more fuel-efficient ones). Vehicle-right-sizing (Table 1) is the idea that AV technology is capable of matching specific vehicles to specific trips. For example, if a party of people calls for a cab, a bigger and more energy-consuming autonomous cab could be sent to them by the cab fleet owner, compared to a situation where only one person calls for a cab. By doing so, fuel-efficiency gains at fleet level will be gained. However, there may be downsides to vehicle design. First, AVs need additional ICT devices which consume energy to produce, and which cost auxiliary power to use. Second, ICT devices, such as GPS antennae or LiDAR (light detection and ranging), could alter the aerodynamic shape of AV vehicles, compared to conventional vehicles, causing higher energy use per kilometer driven, especially while driving at high speeds.

The third mechanism (Table 1), complementary electrification benefits, is the idea that AV technology "*can provide a strong complement to EV technology*" (Taiebat et al. (2018, p. 11453). In Section 3, we will discuss this mechanism in depth.

Finally, the fourth mechanism, is platooning. Broadly speaking platooning is the synchronized movement of two or more AVs trailing each other closely, which reduces aerodynamic drag for the vehicles following on behind. These improved aerodynamics can result in energy savings per kilometer driven for the whole platoon, compared to the vehicles driving separately.

4. Life Cycle Assessment

Quantitatively, the net energy and CO_2 impact of AVs per kilometer driven is still uncertain with estimates that show fuel efficiency improvements per mechanism (listed in Table 1) of a few to sometimes 50%, but also deteriorations in the same order (see, for example, U.S. Energy Information Administration, 2018). Gawron et al. (2018) tried to estimate a net impact

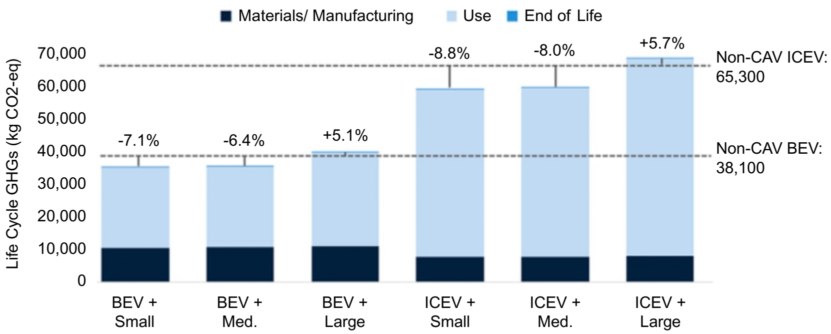

Fig. 1 Life cycle greenhouse gas emissions (GHGs) for six highly automated vehicles. (Gawron et al., 2018).

considering all of these mechanisms by carrying out a Life Cycle Assessment (LCA) of AVs. In the life cycle phases for AVs they included the production, manufacturing and assembly of the materials, the usage and end-of-life management. In Fig. 1 their results for life cycle greenhouse gases[a]tru are given for six of, what they call, AV "scenarios." In these scenarios they combined two propulsion systems with three vehicle sizes. They compared three battery electric AVs (BEV), namely small, medium and large, and three internal combustion engine AVs (ICEV), also small, medium and large with two medium sized non-automated cars, a non-autonomous electric car (lower dotted line) and a non-autonomous ICEV (top dotted line).

A few observations related to Fig. 1 can be made. The most important one is that when comparing the medium-sized, non-autonomous vehicles with the medium-sized AVs, indeed, some net life cycle CO_2 emission reduction can be observed but the impact of high automation is modest with a 6.4% decrease for BEV AVs and 8% decrease for ICEV AVs per kilometer driven. It is important to realize here that the lifetime volume driven for all of the vehicles compared is the same (a 160,000 mile lifetime). In this analysis by Gawron et al. (2018), the relatively modest positive environmental effect of AVs per kilometer driven is in accordance with the previous section: the

[a] Greenhouse gas or CO_2-equivalent emissions is nearly the same for transport as their CO_2 emissions. CO_2 is the dominant greenhouse gas emitted by transport. Other greenhouse gases such as methane (CH_4) and nitrogen dioxide (N_2O) are only emitted in small amounts by transport. Due to these relatively small amounts, they barely count in the CO_2 equivalent, despite the fact that these gases do have a far stronger warming potential compared to CO_2 and, therefore, count relatively heavily in the CO_2 equivalent because this equivalent is a weighted summation of all greenhouse gases emitted according to their warming potential. In the Netherlands, for example, the difference between CO_2 emissions and CO_2-equivalent emissions of road transport is only 1% (https://www.clo.nl/indicatoren/nl013032-emissies-naar-lucht-door-wegverkeer).

net result of an emission increase, due to on-board vehicle subsystems (e.g., more drag due to design issues, data transmission) and, on the other hand, an emission decrease, due to operational effects (e.g., eco-driving, platooning).

The second observation is that when comparing the small, medium and large AV systems there is a significant increase in life cycle CO_2 emissions from medium to large. The reason is the need for a large LiDAR and a more extensive external supporting structure for these larger vehicles which consume a relatively high amount of energy. This observation shows that safety-enabling light-weighting and right-sizing may be very important AV impacts (Table 1) for attaining emission reductions with the AV technology.

The third observation is that the powertrain development—BEV or ICEV—is dominant in achieving relatively high CO_2 emission reductions. However, this shift from ICEVs to BEVs could take place without any AV technology development. Nevertheless, the AV technology may help accelerate this shift (Gawron et al., 2018). Fig. 1 shows that this "accelerating BEV uptake" role of AV technology could be a more significant environmental impact of AV technology, compared to the idea that AV technology in itself is more energy efficient per kilometer driven, compared to non-autonomous technology. In the next section, the role of AVs in potentially accelerating the adoption of battery electric vehicles will be discussed.

5. Electrification

In the literature studied, several arguments are given as to why high automation of vehicles may accelerate a shift from ICEVs to BEVs. The perception that BEVs have a limited driving range is considered to be a major barrier for people buying a BEV (Li et al., 2017). Therefore, one type of argument (based on Brown et al., 2014) as to why AV technology could accelerate BEV uptake is that an electric AV could extend BEV driving ranges by clever route selection. For example, electric AVs can choose routes with fewer stops, which are relatively energy-efficient. Additionally, automation can optimize the driving cycles of BEVs because an algorithm can drive smoother and, thus, more energy efficiently, compared to a human driver. Another idea is that AV algorithms could maximize energy recovery when breaking, resulting in longer BEV driving ranges and even extended battery lives, compared to non-automated vehicles. Related to the potentially positive "right-sizing" impact of AVs (see Section 2), Chen et al. (2016) argue that in a shared autonomous electric fleet, trip matching can take place in order to guarantee that every trip requested (short or long) can be made without the problems associated with the battery running low. By doing so, the range anxiety barrier could be mitigated.

Another type of argument as to why AV technology could accelerate BEV uptake is that AVs might improve BEV economics. Here, the argument is that AVs might increase vehicle utilization rates (see Section 6 below), which "*will improve the economics of low running cost vehicles more than others*" (Offer, 2015, p. 28). Electric AVs are typically expected to be these "low running cost vehicles" due to their expected high utilization rate plus the cost characteristics of BEVs, namely their relatively high purchase costs and low operational costs, when compared to conventional vehicles (Mazur et al., 2018; Offer, 2015; Weiss et al., 2017). The lower operational costs of BEVs can be explained because they have a higher energy conversion efficiency compared to internal combustion engines. Fig. 2 illustrates the relative cost advantages per kilometer driven for high mileage BEVs.

AV technology can have other positive impacts on BEV usage which might also accelerate BEV adoption. Iacobucci et al. (2018, 2019) found in their modeling studies that by optimizing shared autonomous electric vehicle (SAEV) fleets, the charging costs of EVs can be significantly reduced

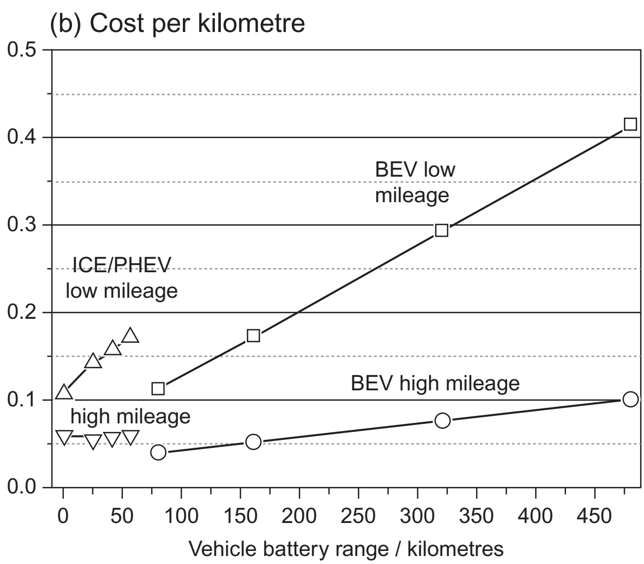

Fig. 2 Cost per kilometer ($/km) for hybrid cars (Internal Combustion Engine combined with a Plug-in Electric motor, ICE/PHEV) and for BEVs. "Low" yearly mileage of 13,216 km is compared to a vehicle utilization rate increased by 5 times to a "high" yearly mileage of 66,064 km (Offer, 2015).

compared to a non-autonomous fleet (SEV). The reason they give is that the charging costs of EVs are dependent on the variable electricity prices. Due to the automation of SEVs, the SAEV fleets can charge more easily at low electricity prices. Iacobucci et al. (2019) indicate that by using historical electricity price data from Japan, the charging costs for SAEV fleets can be reduced by 10% compared to the current charging strategy of SEVs. In the future, vehicle automation can create even more cost advantages, as it is expected that electricity prices will become more volatile (Iacobucci et al., 2018, 2019).

AV technology could even accelerate wider adoption of solar and wind power because electric AVs might be able to participate in the development of so-called vehicle-to-grid (V2G) technology (Lam et al., 2016). V2G technology entails the possibility of bidirectional electricity flows between EVs and the electricity network (Tan et al., 2016). This bi-directionality allows renewable energy to be stored in the EV when it is abundant and to be made available to the grid when the solar and wind power generation output is low. According to Römer et al. (2012), V2G enables storage of excess energy, balancing supply and demand in a flexible way and, therefore, makes the increase of the amount of renewable energy in the electricity network feasible. The idea is that AVs can be programmed to park in the right location to fully support V2G services where and when needed (and at the highest electricity price). Also, algorithms in electric AVs could efficiently deal with bidirectional flows between the vehicle and the electricity grid and the transport of passengers. Especially when large fleets of SAEVs become popular, these algorithms might create a flexible and decentralized storage facility. Anderson et al. (2016) even argue that if AVs were fully integrated, wireless V2G services could become available and make V2G technology more flexible. So, if electric AV technology allows improved V2G usage, two mechanisms can be distinguished which would promote extra environmental benefits. First, the balancing role of electric AVs supports the economics of sustainable energy sources, such as wind and solar, which might result in a higher usage of these technologies. Second, electric AV owners can receive remuneration from the grid operators when they deliver this service to the grid, which makes the electric AVs economically attractive to potential buyers and, because of this, an accelerated uptake of these electric and environmentally friendly vehicles (which use more and more sustainably-produced electricity according to the first mechanism) may take place.

It should be noted that this potential accelerating role of highly automated vehicles for the adoption of BEVs and, possibly, more wind and solar power, is dependent on the speed of development and adoption of highly automated vehicles. Right now, all over the world the deployment of policies to stimulate the sales and use of BEVs seem to have taken off. According to IEA (2018, p. 10): "*the strongest current policy signals emanate from electric car mandates in China and California, as well as the European Union's recent proposal on carbon dioxide (CO_2) emissions standards for 2030.*" If the BEV breakthrough is relatively fast in the next few decades because of deployment of these EV policies, but the high automation AV breakthrough is relatively slow, the accelerating role of AVs with regards to more environmentally friendly technologies will be modest.

6. AVs impact on vehicle kilometer traveled

The CO_2 emissions of road transport is the result of the CO_2 emission factor (g/km traveled) multiplied by the kilometers driven (Vehicle Kilometer Traveled, VKT). In a recent review of AV modeling studies (Soteropoulos et al., 2019) it has been shown that in many instances it is expected that AVs will increase vehicle kilometers traveled and reduce public transport and slow modes shares. In Table 2, some recent volume studies are presented. The general message is clear: they expect an increase in VKT after AVs have been adopted compared to a business-as-usual scenario. Altered generalized costs for AV travel compared to non-autonomous car travel, such as lower value for travel time savings and lower operating costs for AVs, partially explain this increase. Additionally, AVs may lead to extra VKT because new car trips can be made by people who are currently unable (or not allowed) to travel by car, such as disabled people, children, and people who have consumed alcoholic beverages. Finally, VKT may rise due to AV technology because empty trips are possible during which AVs are relocating to other customers, or they are looking for a parking spot, for example.

The only studies that indicate that AVs might decrease VKT assume that large shared automated vehicle fleets will arise because many people are willing to share rides (Soteropoulos et al., 2019). However, it is yet unknown whether many people are, indeed, really willing to share rides. In their study, Lavieria and Bhat (2019) identified that privacy concerns are currently discouraging individuals from using pooled ride-hailing services. They think that privacy-sensitivity may be worsened in a shared AV context because individuals may find themselves alone with a stranger in a vehicle without the presence of a professional driver, as is the case in private ride-hailing services. Their results show that potential "*users are less sensitive to the presence of*

Table 2 An overview of AV literature on the impacts of vehicle kilometers traveled (VKT).

	VKT increase	Cause of Increase	Method
Zhao and Kockelman (2018)	20%	Relatively low values of travel time; relatively competitive pricing. Both result in greater demand for longer distance travel and less transit system use. Empty-vehicle travel for self-parking.	Case study with travel demand model
Kröger et al. (2019)	2.4% or 8.6% Germany 3.4% or 8.6% USA	New automobile user groups, e.g., travelers with mobility impairments. Altered generalized costs of travel, e.g., due to a lower value of travel time savings for car travel.	Scenario analysis with demand model
Lu et al. (2018)	Roughly 30%	Unoccupied vehicle travel (routing, relocation, parking)	Agent-based modeling
Taiebat et al. (2019)	2–47% for an average household	Lower marginal cost of VKT	Microeconomic modeling
Moreno et al. (2018)	8%	Unoccupied vehicle travel (routing, relocation, parking)	Stated Preference
Harb et al. (2018)	83%	Possibility to multitask, zero occupancy rides, added convenience.	Naturalistic experiment
Kloostra and Roorda (2019)	9%	Increased demand Unoccupied vehicle travel (routing, AVs prefer highways)	Demand modeling

strangers when in a commute trip compared to a leisure-activity trip" (p.). Also, the strength of AVs' promise to make time more productive can be somewhat weakened by pooled AV ride-hailing because some sort of social interaction is perhaps required. Indeed, high income groups demonstrate high pooling aversion in all dimensions (Lavieria and Bhat, 2019).

7. Conclusion and policy implications

According to scientific literature the impact of highly automated vehicles on CO_2 emissions per kilometer driven seems modest. With this modest improvement of CO_2 emission per kilometer traveled and a modest to, even, high expected growth in VKT compared to business as usual, the net energy and CO_2 balance for AVs seems at its best neutral but is probably negative. The potentially accelerating role of AVs in relation to the uptake of electric vehicles might potentially have the biggest impact on the CO_2 emissions per kilometer driven, but this accelerating role in the uptake of electric technology is uncertain. Thus, the final picture for the environmentally friendliness of highly automated AVs compared to non-autonomous vehicle development seems not too favorable. In their review, Wadud et al. (2016) came to more or less the same conclusion. They think that at relatively low levels of automation, modest energy savings could be realized. Yet at a high level of automation (the topic of this chapter) they also identify the possibility of substantial increases in travel activities and, thus, in net energy consumption.

What are the policy implications? First, from a CO_2 emission reduction point of view, a shift from fossil-fueled internal combustion engines to electric vehicles is most effective. AV technology might accelerate this shift but to introduce specific policies to already focus on this accelerating role, seems premature right now. It seems more useful to just continue putting policies in place to promote alternative vehicle propulsion systems other than fossil fuel technologies. For example, policies such as the European CO_2 emission standards for new cars, that has already been mentioned, and all kinds of tax and/or subsidy policies to give EVs price advantages compared to fossil fuel technologies. If, in the meantime, AV adoption goes faster than expected, this technology will at least support the shift from fossil fuels to electricity. Second, when the adoption of electric AVs progresses, policies could be implemented which would result in the highest energy-efficiency possible because the electricity (even that produced by solar and wind) which the AVs will use, will also have external costs which politicians might want to internalize. Sections 3 and 4 showed that the energy use (and CO_2 emission) for electric AVs per kilometer driven are, among other things, dependent on clever eco-driving algorithms, right-sizing, potentially negative aerodynamic drag, speed, and so forth. So policies could be put in place, such as energy taxes and AV maximum speed limits, in order to introduce incentives to the market to become as fuel-efficient as possible.

Finally, there seems to be a need for policies which can curb the growth of VKTs due to AV technology, since this growth can result in a very steep increase in marginal external costs of road transport from a policy perspective. It should be noted that this chapter is about only one sort of external transport costs, namely CO_2 emission and external costs of electricity production. Compared to other external costs of a high growth in AV kilometers traveled, such as congestion, these costs might be relatively small. It therefore seems important to develop policies to internalize the external costs of AVs, such as road pricing and/or congestion pricing (for an example see Millard-Ball, 2019), from a broader perspective than solely the environmental costs. Still, perhaps some form of road-pricing for AVs might also help to manage the energy use and CO_2 emissions of AVs.

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