THE CONTRIBUTION OF NEW MOBILITY TECHNOLOGIES AND SERVICES TO CLIMATE CHANGE MITIGATION AND ECONOMIC WELFARE

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Overview

Human-induced climate change is one of the biggest challenges facing humankind today. The causes of global warming lie in rising greenhouse gas (GHG) emissions from anthropogenic sources and its mitigation, through decarbonization of our societies and change in our habits, has become increasingly urgent. Decarbonization of transportation is considered more complex than other energy end-use sectors because existing mobility technology is highly locked in the use of fossil fuels (Pietzcker et al., 2014). In addition, agents' behavioral decisions about transportation and their impacts on energy consumption must be considered when implementing decarbonization policies. Therefore, in order to effectively decarbonize transportation, it is necessary to not only deploy cleaner technologies and fuels, but also promote the behavioral change of agents towards more sustainable mobility products.

At the same time, mobility is also going through its own transformation. When applied to passenger road transportation, the mobility-as-a-service (MaaS) concept, which changes the focus of transportation to service from ownership, has resulted in alternative mobility services such as carsharing, ride-hailing, and automation, which will have a significant impact on the way people move. When properly directed and regulated, these alternative mobility services and technologies can contribute to a more efficient and sustainable use of transportation through reduction of vehicle ownership and promotion of modal shift, with consequent impacts in terms of energy consumption and greenhouse gas emissions. Moreover, through their influence on the choice of transport modes, these alternative technologies and services will also affect users' welfare.

This study, hence, analyzes current literature on new mobility technologies and services in passenger road transportation to assess how these innovations may contribute to changes in vehicle use and ownership as well as adoption of alternative services, with consequent impacts in terms of energy use, its associated emissions, transportation decisions, and overall economic welfare of the population. Such an analysis is important because transportation's energy consumption derives from the behavioral decision of agents, which impacts their welfare. This way, in order to fully understand how alternative mobility technologies and services will develop in an effective way in terms of climate change mitigation, all these factors must be evaluated in conjunction.

This paper is structured as follows: the next section provides an overview of alternative mobility technologies and services, while the following section presents the results of the analysis of how new mobility technologies and services affect energy use, emissions, and economic welfare, and also discusses gaps in the literature. Finally, the last section closes this paper and details future work.

Mobility market trends for alternative technologies and services

Mobility has experienced several changes in the past few years. While carsharing and ride-hailing are common throughout the world, full autonomous vehicles (AVs) have yet to become available for purchase by consumers (although level 2 automation is available in some vehicles today – see Table 2).

Ride-hailing services match drivers and passengers through an online platform or mobile application. The possibility of sharing rides is also available in some locations. Nowadays, some form of ride-hailing service, such as transportation network companies (TNC: Uber, Lyft, among others), regular taxi services (booked online/on app), or ride pooling services (such as Waze Carpool, Via, etc.) has been operating in more than 150 countries, having served more than one billion users (Marciano, 2016; Statista, 2020). Number of users is expected to reach 1.5 billion in 2023 (Statista, 2020).

Carsharing has also became ubiquitous, being present in 59 countries[1] with more than 15 million members sharing over 157,000 vehicles[2]. There are two type of services available: two-way (or station-based), in which users return the vehicle to the same location where the trip started; and one-way (or free-floating), in which the return point can be anywhere within a service area. Table 1 lists different carsharing business models available today.

Table 1: Carsharing's business models. Source: adapted from (Shaheen et al., 2019)

Business-to-consumer (B2C): a carsharing provider offers individual consumer access to a business-owned fleet of vehicles through memberships, subscriptions, user fees, or a combination of pricing models. Example: Zipcar.
Business-to-Government (B2G): carsharing providers (typically, a B2C company) offer transportation services to a public agency. Pricing may include a fee-for service contract, per-transaction cost, or some other pricing model.
Business-to-Business (B2B): carsharing providers (also B2C companies) sell business customers access to transportation services either through a fee-for-service or usage fees. The service is typically offered to employees to complete work-related trips.
Peer-to-Peer (P2P): also known as personal vehicle sharing. A service operator facilitates the match between vehicle owners and guests by providing the organizational resources needed to make the exchange possible. Pricing and access to vehicles vary, being determined by vehicle owners. The service operator generally charges a fee (a percentage of the transaction amount) in return for facilitating the match and providing third-party insurance.

Table 2 describes different levels of automation for vehicles. Full automation is expected to become available for consumers sometime within the next decade (Shaheen et al., 2018b). Nowadays, however, some pilot projects have been testing full AV functionalities in several countries. While pilot projects and technology development have positive impacts on adoption levels, consumer acceptance and legislation/regulation also are important factors for AVs development (KPMG, 2019).

Table 2: Levels of driving automation in vehicles. Source: adapted from (SAE International, 2018).

Level 0 – no driving automation: the driver performs the entire driving task, even when aided by active safety systems.
Level 1 – driver assistance: a driving automation system executes either steering or acceleration/deceleration (but not both simultaneously) with the expectation that the driver performs the remainder of the driving task.
Level 2 – partial driving automation: a driving automation system executes both steering and acceleration/deceleration with the expectation that the driver detects objects and events, answers appropriately and supervises the system.
Level 3 – conditional driving automation: the system performs the entire driving task, but the driver has to be ready to intervene when the system asks to (user becomes driver during fallback: performance-relevant system failure or operational design domain exit).
Level 4 – high driving automation: the system performs the entire driving task (also during fallback) without any expectation that a user will respond to a request to intervene. The driving task, however, is limited by an operational design domain (the system is designed to operate under certain conditions: environmental, geographical, and time-of-day restrictions, and/or presence/absence of certain traffic or roadway characteristics).
Level 5 – full driving automation: the sustained and unconditional (not limited by operational design domain) performance by a driving system of the entire driving task and fallback without any expectation that a user will respond to a request to intervene.

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[1] As of May 2019 (movmi Shared Transportation Services Inc., 2019).

[2] As of 2016. Numbers reflect business-to-consumer (B2C) roundtrip and one-way carsharing only. (Shaheen et al., 2018a).

Results of the analysis

Alternative mobility technologies and services offer different and additional transportation options for consumers to choose, thus affecting economic welfare, energy use and emissions in numerous ways. Understanding such impacts is important so that policy can be designed to foster energy efficiency, sustainable mobility and contribute to mitigate the effects of climate change. For such, we perform a vast literature review to identify the types of impacts covered in each reference, as presented in Table 3. We divide the analysis by type of technology/service (carsharing, ride-hailing, and autonomous vehicles). Most studies focus on the impacts on vehicle ownership, kilometers/miles traveled, emissions, other transit modes and economic welfare.

Table 3: Topics covered in literature by reference

Study	**Impacts on**							
	Vehicle Ownership	**VKT/VMT**	**Fuel efficiency**	**CO$_2$ emissions**	**Safety**	**Other transit modes**	**Economic welfare**	**Other impacts**
Carsharing								
(Kumar Mitra, 2021)	-	-	-	-	-	√	√	√
(Sun and Ertz, 2021)	-	-	-	√	-	-	-	-
(Becker et al., 2020)	-	-	-	-	-	√	√	√
(Migliore et al., 2020)	-	-	-	√	-	-	-	-
(Schmöller and Bogenberger, 2020)	√	-	-	-	-	√	√	-
(Te and Lianghua, 2020)	-	-	-	√	-	-	-	√
(Tsuji et al., 2020)	-	-	-	√	-	-	-	√
(Zhou et al., 2020)	√	-	-	-	-	-	-	√
(Ding et al., 2019)	-	-	-	√	-	-	-	-
(Ko et al., 2019)	√	-	-	-	-	-	-	√
(Le Vine and Polak, 2019)	√	-	-	-	-	-	-	√
(Shaheen et al., 2019)	√	√	-	√	-	√	√	√
(Sprei et al., 2019)	-	-	-	-	-		√	√
(Tyndall, 2019)	-	-	-	-	-	√	-	-
(Becker et al., 2018)	√	-	-	-	-	√	-	-
(Jung and Koo, 2018)	√	-	-	√	-	-	-	√
(Namazu and Dowlatabadi, 2018)	√	-	-	-	-	√	-	√
(Nijland and van Meerkerk, 2017)	√	√	-	√	-	√	-	-
(Chen and Kockelman, 2016)	-	-	√	√	-	-	-	-
(Clewlow, 2016)	√	√	-	-	-	√	-	√
(Giesel and Nobis, 2016)	√	-	-	-	-	-	-	-
(Rabbitt and Ghosh, 2016)	-	-	-	√	-	√	√	√
(Baptista et al., 2014)	√	-	√	√	-	√	√	√
(Costain et al., 2012)	-	√	-	-	-	√	-	√
Ride-hailing								
(Schaller, 2021)	-	√	-	-	-	√	-	√
(Tarduno, 2021)	-	-	-	-	-	-	√	-
(Ward et al., 2021)	√	-	√	-	-	√	-	-
(Wu and MacKenzie, 2021a)	√	√	-	-	-	√	-	-
(Wu and MacKenzie, 2021b)	-	√	-	-	-	-	-	-
(Baker, 2020)	-	-	-	-	-	√	-	-
(Bekka et al., 2020)	√	√	-	-	-	-	-	-
(Jenn, 2020)	-	-	-	√	-	-	-	√
(Jiao et al., 2020)	-	√	-	-	-	-	-	√
(Roy et al., 2020)	-	√	-	-	-	√	√	-
(Sabouri et al., 2020)	√	-	-	-	-	-	-	-
(Tirachini, 2020)	√	-	-	√	-	√	√	√
(Tirachini et al., 2020)	-	√	-	-	-	√	-	-
(Yi and Yan, 2020)	-	-	-	√	-	-	-	-
(Young et al., 2020)	-	-	-	-	-	√	√	-
(Cai et al., 2019)	-	√	-	√	-	-	-	-
(Habib, 2019)	-	-	-	-	-	√	-	-
(Haddad et al., 2019)	-	-	-	-	-	√	√	√
(Henao and Marshall, 2019)	√	√	-	-	-	√	-	√
(Malalgoda and Lim, 2019)	-	-	-	-	-	√	-	-
(Sui et al., 2019)	-	-	-	√	-	-	-	√
(Tirachini and del Río, 2019)	-	-	-	-	-	√	√	√
(Ward et al., 2019)	√	√	-	√	-	-	√	-
(Wenzel et al., 2019)	-	√	√	-	-	-	-	-
(Young and Farber, 2019)	-	-	-	-	-	√	-	-
(de Souza Silva et al., 2018)	-	-	-	-	-	√	√	√
(Hall et al., 2018)	-	-	-	-	-	√	√	-
(Rodier, 2018)	√	√	-	-	-	√	-	-
(Schwieterman and Smith, 2018)	-	-	-	-	-	-	√	√
(Vanderschuren and Baufeldt, 2018)	-	-	-	-	-	-	√	√
(Wu et al., 2018)	-	-	-	√	-	√	-	-
(Yin et al., 2018)	-	-	-	√	-	√	√	√

Autonomous vehicles (AVs)								
(Oh et al., 2021)	-	√	-	√	-	-	√	-
(Alarfaj et al., 2020)	-	-	-	√	-	-	-	√
(Brown and Dodder, 2019)	-	-	-	√	-	-	√	-
(Gawron et al., 2019)	-	-	-	√	-	-	-	-
(Gelauff et al., 2019)	-	-	-	-	-	√	√	-
(Jones and Leibowicz, 2019)	-	-	√	√	-	-	√	√
(Kröger et al., 2019)	-	√	-	-	-	√	-	√
(Liu et al., 2019)	-	√	√	√	-	-	-	-
(Patella et al., 2019)	-	√	-	√	-	-	√	-
(Sethuraman et al., 2019)	-	-	√	-	-	-	-	√
(Soteropoulos et al., 2019)	√	√	-	-	-	√	√	√
(Stogios et al., 2019)	-	-	-	√	-	-	-	-
(Taiebat et al., 2019)	-	√	-	-	-	-	√	-
(Venturini et al., 2019)	-	-	-	√	-	√	√	-
(Zhang et al., 2019)	-	-	-	√	-	-	-	√
(Fox-Penner et al., 2018)	-	√	√	√	-	-	-	-
(Gawron et al., 2018)	-	-	-	√	-	-	-	-
(Hidaka and Shiga, 2018)	-	-	-	-	-	√	√	-
(Taiebat et al., 2018)	-	√	√	-	√	√	√	√
(Vahidi and Sciarretta, 2018)	-	-	√	-	-	-	-	-
(Kockelman et al., 2017)	√	√	-	-	√	-	√	-
(Milakis et al., 2017)	√	√	√	√	√	√	√	√
(Ross and Guhathakurta, 2017)	-	√	-	-	-	-	-	-
(Stephens et al., 2016)	-	√	√	-	-	-	√	-

More detailed information on each study can be found in Table A 1 in the Annex, while Table 4 summarizes the results. Given that the studies analyzed use different methods to assess these impacts, the numerical ranges reported in Table 4 are merely for illustrative purposes. Nonetheless, a trend is observed for each technology/service analyzed. Overall, direction of effects is fairly the same across studies, but their magnitude is influenced by assumptions made.

Table 4: Overall impact of new mobility technologies and services

Vehicle Ownership	VKT/VMT	CO_2 emissions	Other transit modes	Economic welfare
Carsharing				
Lower vehicle ownership across studies (range: 3 – 80% reduction)	**Lower** VKT/VMT across studies (range: 2 – 83% reduction)	**Lower** emissions across studies (range: 4 – 67% reduction)	- **Increases** public transit and active modes' use - **Complements** transit (fills gaps) - **Substitutes** private/rented cars	**Increases** welfare: more access to households, fills mobility gaps, cheaper than vehicle ownership
Ride-hailing				
Inconclusive, but there is a negative trend among users (either reduced car ownership or intention to shed a vehicle)	**Higher** VKT/VMT across studies (range: 8 – 157% increase), mostly due to deadheading	**Lower** emissions, which are mostly due to the modelling of shared/pooled services and EVs across studies	Mostly **substitutes** modes. Results across studies: - Public transit: 17 – 31% - Public transit and active modes: 34 – 58% - Private cars and taxis: 19 – 83%	**Increases** utility for users and grants positive externalities, but also **increases** congestion and **reduces** traffic speed, which may negatively impact welfare
Autonomous vehicles				
Not much studied. Some papers show that shared autonomous vehicles (SAVs) decrease ownership	**Higher** VKT/VMT across studies (range: 2 – 47% increase). SAVs mitigate impacts	**Lower** emissions across studies (range: 3 – 87% reduction) when performance is optimized, increased fuel efficiency, etc.	**Substitute** public transit and active modes	**Increase** welfare for users and reduce system's operating costs. May increase congestion, but impact is mitigated with SAVs

The extent of carsharing's impacts varies across studies due to several factors: region; density; built environment; public transit accessibility; and carsharing service and business model (Shaheen et al., 2019). Overall, carsharing leads to reduced vehicle ownership. Users report that they have already sold, will sell their private cars or have given up the idea of buying a vehicle. Less vehicles impact kilometer/miles travelled and emissions, which shows that carsharing provides a good alternative to improve the efficiency of transportation. Moreover, fuel efficiency is improved if the carsharing fleet is comprised of more energy efficient vehicles, such as hybrids and battery electric vehicles (BEVs) (Baptista et al., 2014). Greater emission reduction is also achieved with EVs in the carsharing fleet (Jung and Koo, 2018).

Regarding interaction with other transit modes, some studies report that, depending on the trip's characteristics, carsharing increases the use of transit and active transportation modes, substitutes private/rented cars, and complements public transportation. By filling gaps in transit supply, carsharing increases the welfare of the population (Costain et al., 2012; Schmöller and Bogenberger, 2020). Greater access, especially to lower income households, which cannot afford car ownership, is another positive welfare impact of carsharing (Kumar Mitra, 2021; Shaheen et al., 2019). The carsharing type of service also affects results. (Namazu and Dowlatabadi, 2018) compare users of free-floating and two-way carsharing services, which are used differently: the former group is more likely to use the service as a complement to all modes of transportation, while the latter is more likely to use carsharing as a substitute for private car ownership. (Schmöller and Bogenberger, 2020) report that free-floating carsharing is used for commuting or leisure trips (going to restaurants, dancing, etc.), while two-way carsharing is used for weekend trips and longer-term needs. (Sprei et al., 2019) reports that given the higher cost per trip compared to other modes, and no major time gain, carsharing provide some extra utility to users. This way, the use of carsharing in an efficient transportation system must consider users' preferences: customers will choose transportation based on economic and time costs, but also based on the errand that must be ran.

Preferences are a big determinant for the expansion of ride-hailing. Review from the literature found that ride-hailing mostly substitutes other transit modes and increase VKT/VMT, especially due to deadheading (empty vehicle miles/kms driven between trips). As a result, cities have been experiencing more congestion and reduced traffic speed. The negative impact of deadheading, however, is lower when ride-hailing services (e.g.: Uber) substitute taxis, which have higher deadheading rates (Sui et al., 2019; Tirachini, 2020). Although energy consumption impacts are not ideal, ride-hailing has expanded due to the utility it provides to users. For instance, in Brazil, ride-hailing is used as an alternative to unsafe transportation modes such as walking and public transit (de Souza Silva et al., 2018). (Vanderschuren and Baufeldt, 2018) discuss the social benefit of ridesharing when it counters for insufficient mobility services in Cape Town. (Habib, 2019) also reports that ride-hailing fills gaps in public transit in the Greater Toronto area. For ride-hailing users, time savings are a welfare gain (Schwieterman and Smith, 2018; Tirachini, 2020). These welfare gains potentially affect the economy. In São Paulo, Brazil, ride-hailing positively impact accessibility of workers in the job market, thus enhancing economic activity (less time wasted commuting increases workers' productivity) (Haddad et al., 2019). (Tarduno, 2021) reports that congestion costs are similar in magnitude to the consumer surplus provided by ride-hailing. Therefore, the design of an effective sustainable transportation system must account not only for its energy impacts, but also for the benefits it brings to society.

Autonomous vehicles are also expected to benefit society in numerous ways. AVs will provide mobility to underserved populations, like the disabled, elderly, and children; will reduce the opportunity cost of travelling because it will allow to multitask while on board; will improve security and efficiency of travel; among others. The aforementioned factors, however, may substantially increase VKT/VMT, energy use and emissions (impacts that are mitigated when shared AVs are considered and performance is optimized). AVs may also contribute to urban sprawl, job displacement and unemployment[3]. (Taiebat et al., 2018) review several publications about AVs from four perspectives: vehicle, transportation system, urban system, and society levels. While they foresee positive environmental impacts at the vehicle, transportation, and urban system levels, greater vehicle utilization and shifts in travel patterns at the society level may offset some of the benefits. In addition, they argue that "Focusing on the vehicle-level improvements associated with connected AV technology is likely to yield excessively optimistic estimates of environmental benefits." (Taiebat et al., 2018). (Milakis et al., 2017) also claim that AVs' effects on

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[3] A publication from the (U.S. Department of Energy, 2017) states that, in the medium to longer term, if manufacturers adjust their production according to the new demand (either lighter, less complex cars, or more durable and resistant cars), an equilibrium in the vehicle manufacturing market is reached.

safety, economy, public health and social equity are still unclear. Hence the importance of discussing the transition to a sustainable transportation system in a holistic way, considering welfare and energy impacts in conjunction.

Some studies, however, have tried to shed light on the effects autonomous vehicles may have in the economy through impacts on agents' welfare. (Gelauff et al., 2019) simulate spatial effects of autonomous vehicles for the Netherlands. Using a general equilibrium model, they analyze how more productive time use during car trips and fast and comfortable door-to-door automated public transit affect welfare. Their results report that the car component results in population flight from cities, while the public transit component leads to population clustering in urban areas. Moreover, a combination of both components may result in population concentration in the largest, most attractive cities, at the expense of smaller cities and non-urban regions: "The simulations suggest that welfare benefits of automation are considerable, with up 10% coming from population relocation and changes in land use." (Gelauff et al., 2019). In sum, relocation causes increased utility (people are moving because they are better off this way) and welfare.

(Soteropoulos et al., 2019) review several modelling studies investigating the impacts of AVs on travel behavior and land use and conclude that shared autonomous vehicle fleets could have positive impacts such as, for instance, reducing the overall number of vehicles and parking spaces. Moreover, if assumptions consider that automation leads to a more efficient public transport system, AVs could lead to a favoring of urbanization processes. These results, however, are too sensitive to assumptions, hence the need to develop more studies to evaluate all these variables concurrently: how the employment of all new mobility technologies simultaneously may impact energy systems and the economy through energy consumption, emissions, and the welfare of agents.

(Jones and Leibowicz, 2019) use an energy systems model (OSeMOSYS) to integrate the electricity and transport sectors, while also computing endogenous technology adoption, to explore the contributions of SAVs to climate change mitigation, but their analysis does not further assess what impact SAVs will have on the economy as a whole. Such an analysis is important because energy and transportation consumption derives from the decision of agents, which impact their welfare. This way, in order to fully understand how alternative mobility technologies and services will develop in an effective way, so that they can truly contribute to climate change mitigation, an economic analysis must be performed along with an energy optimization study.

Conclusion

The impacts of alternative mobility technologies and services on energy consumption and emissions have been largely studied. While the promotion of these services may be policy driven, there is no approach, however, that considers the two perspectives of energy use and economic welfare. By impacting the welfare of agents, new mobility technologies that are employed as policy solutions to improve energy consumption may further affect productivity and the economy. Such outcomes have yet to be measured and are under development by the authors. This upcoming analysis will develop a hybrid energy system/macroeconomic model where a representative agent will make transportation and energy consumption decisions, which will affect energy demand and, consequently, energy supply, emissions, prices, and welfare. Alternative mobility technologies and services will be available for agents to choose as part of the transportation sector within the energy systems model. The upcoming study aims to assist policy makers in the design of a transportation system in line with climate change mitigation efforts.

Acknowledgments

The authors acknowledge Fundação para a Ciência e Tecnologia for IN+ Strategic Project UID/EEA/50009/2019 and for contract CEECIND/02589/2017.

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Annex

Table A 1: Literature review of new mobility technologies and services' impacts on several variables

Study	**Objective**	**Type of study/Methods**	**Impacts on**							
			Vehicle Ownership	**VKT/VMT**	**Fuel efficiency**	**CO$_2$ emissions**	**Safety**	**Other transit modes**	**Economic welfare**	**Other impacts**
Carsharing										
(Kumar Mitra, 2021)	Examine the impact of carsharing on the mobility of lower-income populations in California	Structural Equation Modeling	-	-	-	-	-	Carsharing's benefits for lower-income households are optimized when combined with local public transportation	Carsharing has a stronger effect on the mobility of lower-income than higher-income households. Financial barriers (user cost, lack of bank accounts) predict more access to service than physical availability	Carsharing adoption is influenced by the frequency (micro-accessibility) of public transportation
(Sun and Ertz, 2021)	Explore how mutualized mobility (carsharing, carpooling and ride-hailing) contribute to reduce GHG emissions of urban transportation in Beijing* and Toronto in 2016 (from 2011 levels) *Just ride-hailing is analyzed	Simulation (Life cycle assessment (LCA) model)	-	-	-	Toronto: annual per capita GHG emissions fell by 2.8 kg of CO2-eq –carpooling and car-sharing's contribution was higher than ride-hailing's. Beijing: ride-hailing increased emissions. Ride-hailing's results are due to deadheading, which accounted for about 30% of total vehicle life cycle emissions.	-	-	-	-
(Becker et al., 2020)	Assess the welfare impacts of Shared Mobility and Mobility as a Service (MaaS) in Zurich	Simulation (agent-based microsimulation model)	-	-	-	-	-	Efficiency gains may be higher if shared modes substitute public transport in lower-density areas	Carsharing and bike-sharing may increase transport system efficiency (travel time and costs) by up to 7%	Transport-related energy consumption can be reduced by 25%
(Migliore et al., 2020)	Estimate the environmental benefits of carsharing in Palermo	Simulation (accounting model)	-	-	-	Reduction of 25% for PM$_{10}$ and of 38% for CO$_2$	-	-	-	-
(Schmöller and Bogenberger, 2020)	Better understand how carsharing systems work and which problems still exist	Literature review	Carsharing users own less cars than the rest of the population, but it is difficult to assess whether carsharing causes this behavior	-	-	-	-	Among carsharing users, there is a modal shift from private cars to nonmotorized modes or public transport, but impacts are small to	Carsharing fills a mobility gap; free-floating carsharing is used mostly for short-term needs, while station-based is used for long-term needs	-

								extrapolate to the whole population		
(Te and Lianghua, 2020)	Analyze the expansion of the carsharing market and its impacts on GHG emissions and land use in China	Statistical (regression) analysis, accounting methods	-	-	-	Energy savings of ~ 8.45 × 10^8 MJ and up to 4.226 × 10^{10} MJ in 2016 and 2020, respectively; CO_2e emission reduction of 68 ktons and up to 3.4 × 10^6 in 2016 and 2020, respectively	-	-	-	In 2016, parking demand reduction leads to area savings of approximately 327,900 standard football fields, which is expected to grow to up to 1.171 × 10^{11} m^2 in 2020
(Tsuji et al., 2020)	Identify how carsharing affects CO_2 emissions in Japan	Simulation model	-	-	-	The main determinants of CO_2 emissions are the ratio of people who shed their private cars, degree of rebound effect, and size of the carsharing fleet. That is, carsharing must replace private vehicles to impact emissions	-	-	-	Rebound effects of carsharing may counteract environmental benefits
(Zhou et al., 2020)	Examine the impact of car-sharing on private vehicle ownership in Australia	Statistical (logit regression) analysis	Carsharing's availability have minimal impact on survey respondents' decision to own a vehicle or not	-	-	-	-	-	-	Because the majority of respondents did not self-identify as carsharing users, education campaigns could be important policy tools
(Ding et al., 2019)	Understand how carsharing may contribute to reduce the emission of global warming potential (GWP) gases of urban transportation in Beijing	Simulation (Life cycle assessment (LCA) model)	-	-	-	Emissions of GWP gases, in CO_2eq, are reduced by ~4% and ~20% when carsharing replaces ~10% and ~50% of private cars, respectively	-	-	-	-
(Ko et al., 2019)	Identify factors that affect carsharing program participants' car ownership status in Seoul	Statistical analysis	About 30% of members have changed or plan to change vehicle ownership. In particular, 2.3% had already shed their cars, resulting in a replacement rate of 3.3 private cars / shared car	-	-	-	-	-	-	Carsharing use and decision to shed a private car is affected by: parking availability, access to carsharing stations, household income
(Le Vine	Establish the impact of free-floating	Survey analysis	83% of users decided not to buy a car, 11%	-	-	-	-	-	-	Average income and education level of

and Polak, 2019)	carsharing on private car ownership in London, UK		reported disposing of a car, and 6% will sell a private car							users are both higher than for the general population. And, among heavier users, car ownership impacts are larger
(Shaheen et al., 2019)	Literature review of carsharing's impacts and trends for the future	Literature review	Sold vehicles or delayed/foregone vehicle purchases (2%-71%, depending on business model)	Reduced (3%-80%, depending on business model)	-	Reduced (e.g.: 34%-41% per household in the U.S.; 39%s-54% in Europe)	-	Increased use of some alternative transportation modes (e.g., walking, biking)	Increased access and mobility for formerly carless households; savings compared to car ownership	Greater environmental awareness
(Sprei et al., 2019)	Analyze whether free-floating carsharing contributes to low-carbon mobility and mode displacement	Survey analysis of travel time and usage patterns from 12 cities in Europe and the U.S.	-	-	-	-	-		Given the higher cost per trip compared to other modes, and no major time gain, carsharing provide some extra utility to users	Service is mainly used for one-way trips; median rental time is close to 30'; actual driving time is closer to 15'; BEVs are used for shorter trips
(Tyndall, 2019)	Provide empirical evidence of significant interaction between public transit and carsharing	Statistical (regression) analysis using data from a natural experiment (failure of the public transit rail system in Vancouver)	-	-	-	-	-	Carsharing substitute public transit trips when there are delays in the latter	-	-
(Becker et al., 2018)	Measure the car ownership impact of free-floating car-sharing in Basel	Statistical (difference-in-differences) analysis	6% of the free-floating car-sharing customers reduce their private vehicle ownership	-	-	-	-	Free-floating car-sharing both complements and competes with station-based car-sharing and also triggers a modal shift towards public transportation	-	-
(Jung and Koo, 2018)	Investigate the environmental impacts of carsharing services in South Korea	Statistical (regression) analysis	Probability of forgoing an owned vehicle may reach 16%	-	-	Replacing public transit and private vehicles by carsharing offsets GHG emissions reduction. But if carsharing vehicles are EVs, emissions can get to zero	-	-	-	Increased carsharing flexibility (one-way and delivery services) leads to more carsharing use
(Namazu and Dowlatabadi, 2018)	Investigate how membership in different carsharing business models impact vehicle ownership among users in Vancouver	Statistical (logit regression) analysis	Reduction of 12% (free-floating), 36% (two-way) and 35% (both services)	-	-	-	-	Free-floating users are more likely to complement all transport modes, while two-way users substitute private cars	-	Two-way users were roughly five times more likely to reduce car ownership compared to free-floating users
(Nijland and van Meerkerk, 2017)	Quantify the effects of car sharing on car ownership, car use and CO2 emissions in the Netherlands	Counterfactual analysis based on a survey amongst car sharing users	30% less car ownership among users; service mostly replaced a 2^{nd} or 3^{rd} car	15%–20% fewer VKT	-	Between 240 and 390 fewer kgs of CO2/person/yr. From this, about 1/3 to half is due to less car use; the rest to reduced car ownership	-	Service is mostly substituting train, borrowed/rented cars	-	-

(Chen and Kockelman, 2016)	Examine carsharing's impacts on energy use and GHG emissions among candidate users in the U.S.	Simulation. Scenarios are estimated based on findings from existing literature	-	-	Improved: energy reduction between 33%-70%, depending on scenario	Reduced (33%-67%, depending on scenario)	-	-	-	-
(Clewlow, 2016)	Analyze the effects of carsharing on travel behavior and vehicle ownership among carshare members in the San Francisco Bay Area	Survey analysis (utilizing data from the 2010–2012 California Household Travel Survey (CHTS))	Lower household vehicle ownership in dense urban neighborhoods (0.58 vehicles/household versus 0.96 in the control group)	Lower VMT in the suburbs (average of 15.8 miles per day versus the 23.6 miles per day of a non-member)	-	-	-	Higher modal shares of transit, walking and biking[4]	-	Higher rates of electric drive vehicle ownership (18.3% as compared with 10.2% among non-members)
(Giesel and Nobis, 2016)	Analyze whether free-floating carsharing leads to a reduction of car ownership compared to station-based carsharing in Berlin and Munich	Statistical (regression) analysis	Station-based and free-floating carsharing lead to a reduction of private cars: 7% and 15%, respectively	-	-	-	-	-	-	-
(Rabbitt and Ghosh, 2016)	Estimate scenarios to examine the financial and environmental factors influencing carsharing adoption and use	Simulation scenarios based on literature review and survey of individual travel characteristics in Ireland	-	-	-	Reduction between 14% and 65% among car owners; slight increase for non-car owners	-	Increased share of sustainable modes of travel	Cost savings for car owners between 60-74%; extra costs for non-car owners	"Outside Dublin, there is a lack of high-density areas with suitable users" for carsharing development
(Baptista et al., 2014)	Estimate car sharing impacts and the effects of a possible technology change in Lisbon, Portugal	Simulation and survey analysis	Among users, 8% forfeited ownership of a vehicle after joining the service	-	Improved, if fleet is comprised of hybrid (35%) or battery electric (47%) vehicles	Reduced, if fleet is comprised of hybrid (35%) or battery electric (65%) vehicles. Local pollutant emissions are also reduced	-	Replaces taxis, private cars and subway for some trips, complements public transport for others[5]	Increased, due to reduction in the number of vehicles and their associated costs	Break-even point of a carsharing fleet is influenced by intensity of use, revenues and costs
(Costain et al., 2012)	Understand carsharing behavior in Toronto	Statistical (regression) analysis	-	More VKT is generated when a carbon-offsetting option is offered	-	-	-	Carsharing is mostly used for off-peak travel/on weekends, when transit service is poor and traffic congestion is low	-	Carsharing is preferred by environmentally conscious people; majority of trips are short distance
Ride-hailing										
(Schaller, 2021)	Examine the effectiveness of shared services in reducing vehicle miles traveled (VMT) in four U.S. cities and California suburbs	Literature review and publicly available data review	-	Increases by 97% in Chicago, 114% in New York City, 118% in San Francisco, 157% in Boston and 118% in California suburbs	-	-	-	Shared (pooled) ride-hailing is substituting public transportation, walking and biking	-	Deadheading also contributes to increase shared ride-hailing's VMT
(Tarduno, 2021)	Study the impact of transportation network companies (TNC) on	Statistical (difference-in-differences regression) analysis	-	-	-	-	-	-	TNCs decreased daytime traffic speeds by 2.3%;	-

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[4] "Controlling for carshare-accessible locations, in the Bay Area carshare members made only 41.5% of their trips by car, as compared with 61.8% of non-members. Carshare members made 14.5% of their trips by transit and 34.9% of their trips by walking, as compared with 10.3% and 23.0% of the control population trips, respectively."(Clewlow, 2016).

[5] Carsharing replaced taxi (17%) for both shopping and medical appointment trips, substituted private car for private trips (13%) and subway (8%) for shopping and personal activities trips. In addition, 21% of users started using other transport modes.

	congestion in Austin, Texas								congestion costs range from $33 to $52 million annually, but are similar in magnitude to the consumer surplus provided by TNCs	
(Ward et al., 2021)	Estimate effects of Uber/Lyft market entry on U.S. urban areas	Statistical analysis (difference-in-difference propensity score-weighted regression model)	Vehicle ownership per capita increase by 0.7% on average, being larger in car-dependent and slow-growth cities	-	Increases on average by 0.03%	-	-	Transit ridership decreases on average by 0.09%, being larger in cities with higher income (–5.1%) and with fewer children (–2.6%)	-	-
(Wu and MacKenzie, 2021a)	Explore how taxis and ridesourcing services have evolved from 2001 to 2017 in the USA	Survey analysis	Frequent users had lower vehicle ownership and lower automobile mode share, with a significantly higher share for public and active transportation	Ride-hailing tours (“a sequence of trips to a single or multiple anchor destinations, beginning and ending at home”) grew from 0.4% of all tours in 2009 to 1% of all tours in 2017, mostly within densely populated and transit-oriented regions	-	-	-	One-third of all tours containing ride-hailing also included transit, while 40% of ride-hailing containing tours also involved auto trip(s)	-	-
(Wu and MacKenzie, 2021b)	Estimate the VMT effects of ride-hailing across population groups in the USA	Statistical (Average treatment effect) and Survey analysis	-	Overall, ride-hailing generated a net increase of 7.8 million daily VMT in 2017, which increases with greater deadheading	-	-	-	-	-	-
(Baker, 2020)	Understand how neighborhood characteristics affect ride-hailing use, as well as the relationship between ride-hailing and public transit ridership in San Francisco	Statistical (regression) analysis	-	-	-	-	-	Overall positive relationships between ride-hailing use and public transportation ridership, which varies across the city (not significant in downtown areas, but relevant in choice rider neighborhoods)	-	-
(Bekka et al., 2020)	Investigate Uber’s role in car ownership and its effects on traffic volume in the Paris Region	Survey analysis (Likert scale), statistical analysis (multiple linear regression)	Removal of 3.6 to 4.9 cars per 100 households who have at least one of its members using Uber	Overall impact between -0.6% and +0.9%	-	-	-	-	-	-
(Jenn, 2020)	Understand the emissions benefits of electric vehicles in ride-hailing services in California	Statistical and data analysis	-	-	-	Emission reduction for EVs being used in ride-hailing is approximately three times higher compared to gasoline vehicles	-	-	-	Concerns about the ability of EVs to provide the same level of service as gasoline vehicles has been overstated: there is no statistical difference between the two technologies

(Jiao et al., 2020)	Assess whether usage of shared mobility services induces trip generation	Statistical (regression) analysis	-	Ride-hailing generates trips (mostly on weekdays); bike and carsharing do not	-	-	-	-	-	Females generate more trips; people working from home generate trips on weekdays, while full-time workers do so on weekends
(Roy et al., 2020)	Analyze whether ride-hailing is responsible for increased congestion in San Francisco	Travel demand model	-	Increase of 47%. 70% of in-service ride-hailing vehicles are new vehicle trips that add traffic to the roads	-	-	-	Ride-hailing person trips substitutes 27% of car or taxi trips, 58% of walk, bike or transit trips, while 15% trips are added with no substitution for another mode	Ride-hailing contributes to an increase of 55% in vehicle hours traveled, 51% in vehicle hours of delay, and to 55% in speed decrease	-
(Sabouri et al., 2020)	Examine the relationship between ride-hailing and vehicle ownership in the USA	Statistical analysis and Machine learning method (random forest)	There is a negative correlation between using ride-hailing and vehicle ownership, which is also negatively associated with the number of years Uber has operated in a county	-	-	-	-	-	-	-
(Tirachini, 2020)	Discuss the sustainability and travel behavior impacts of ride-hailing	Literature review	The relationship between car ownership and the intensity of ride-hailing use is still disputed	-	-	"The total effect of ride-hailing on the environment is disputed at this stage"	-	Taxis, public transport and driving personal cars are the modes most substituted by ride-hailing; Ride-hailing can both substitute for and complement public transport, but results on magnitude of impacts are mixed	Reasons to choose ride-hailing: trip cost, travel time, ease of payment, to avoid driving after drinking alcohol, to avoid searching or paying for parking, public transport inconvenience, comfort, security and safety	Mixed land uses increase ride-hailing use. The service is mostly used for occasional trips. Ride-hailing most likely increases motorized traffic in the cities where data are available. Its deadheading rate is lower than taxi's
(Tirachini et al., 2020)	Study the effects of a shared-mobility service that allows users to share rides in a car, van or bus in Mexico City	Survey and scenario analysis	-	Increase of 7 to 10 km/passenger for shared cars; decrease of -0.2 to -1.1 km/passenger for shared vans; increase of 0.4 to 1.1 km/passenger for buses	-	-	-	Individual modes most replaced are metro, buses, car as a driver, ridesourcing/e-hailing and microbus	-	-
(Yi and Yan, 2020)	Evaluate shared mobility's influence on energy consumption, emissions and transportation structure in China	Simulation (Relevance Vector Machine (RVM) model)	-	-	-	Reduction of 518 ktons of CO_2, 31 ktons of CO, 1633 tons of NO_x, 25 tons of $PM_{2.5}$ and 30 tons of PM_{10} in 2018	-	-	-	-
(Young et al., 2020)	Investigate whether ride-hailing trips substitute or complement transit alternatives in Toronto	Statistical (regression) analysis	-	-	-	-	-	Ride-hailing trips demanded during peak hours, or for shopping, are more likely to have transit alternatives of similar duration; 31% of ride-hailing trips	Differences in travel-time often to be caused by transfers and lengthy walk- and wait-times for transit	-

								have transit alternatives of similar duration (≤15-minute difference); 27% of ride-hailing trips have poor transit-based alternatives		
(Cai et al., 2019)	Quantify the environmental benefits of ride sharing in Beijing	Simulation (optimization model)	-	Reduced by 33% (with a rider's tolerance level to trip deviation at 10 min)	-	Annual total reduction of vehicular NO_x, PM_{10}, and CO emissions by 0.24%, 1.4%, and 0.28%, respectively. CO_2 emission reduction is not estimated	-	-	-	-
(Habib, 2019)	Investigate whether Uber competes with other modes in the Greater Toronto and Hamilton Areas	Simulation (choice model)	-	-	-	-	-	There is not any evident competition between Uber and private cars, public transit, or non-motorized modes; Uber tends to fill gaps in transit services	-	-
(Haddad et al., 2019)	Estimates the socioeconomic impacts of ride-hailing in São Paulo	Simulation (Spatial Computable General Equilibrium (SCGE) model)	-	-	-	-	-	83% of trips substitute traditional motorized private modes, the remaining comes from public transit	Productivity gains and improved access of workers lead to reduction of economic and spatial inequality, and increased economic efficiency and activity	Effects on congestion are small
(Henao and Marshall, 2019)	Analyze impacts of ride-hailing on transportation efficiency (deadheading, vehicle occupancy, mode replacement, and vehicle miles traveled (VMT)) in Denver	Ethnographic and survey-based approach	13% of respondents reported owning fewer cars due to ride-hailing	The lower end percentage of deadheading miles from ride-hailing is 40.8%; ride-hailing leads to approximately 83.5% more VMT	-	-	-	Ride-hailing trips substituted: 19% of single-occupancy vehicle trips; 34% of walking, biking, or transit; and more than 12% would not have been taken otherwise	-	The average vehicle occupancy is 1.4 passengers / ride; distance weighted vehicle occupancy is 1.3 (without deadheading) and 0.8 (with deadheading)
(Malalgoda and Lim, 2019)	Examine the effect of TNCs and transit effectiveness on public transit ridership in the USA from 2007-2017	Statistical (regression) analysis	-	-	-	-	-	TNC availability increased rail ridership in 2015; year-by-year, rail transit effectiveness trumped TNC availability; TNCs are neither a complement nor a substitute of bus transit.	-	-
(Sui et al., 2019)	Compare fuel consumption and emissions between ride-hailing and taxis in Chengdu, China	Data analysis	-	-	-	Fuel consumption and CO, NOx, and HC emissions per passenger-on kilometer of taxi trips are about 1.36, 1.45, 1.36	-	-	-	Ride-hailing's emissions are lower because of lower deadheading, compared to taxis

						and 1.44 times that of ride-hailing trips, respectively.				
(Tirachini and del Río, 2019)	Examine the use of ride-hailing in Santiago de Chile	Statistical (regression) analysis	-	-	-	-	-	Modes most substituted are public transport and traditional taxis	Probable increase in traffic because for each rider who combines ride-hailing and public transport, 11 riders substitute the latter	Frequency of use is larger among richer and younger travelers; probability of sharing a trip decreases with household income and increases for leisure trips
(Ward et al., 2019)	Estimate effects of ride-hailing on per-capita vehicle ownership, energy use, travel distances, and emissions in U.S. states (2005-2015)	Statistical analysis (difference-in-difference propensity score-weighted regression model)	Ride-hailing companies' entry in markets reduce state per-capita vehicle registrations by 3%, on average	Not conclusive	-	Volatile organic compounds (VOCs) emissions decrease by 4.8%	-	-	Decrease in vehicle emissions (4.8%) represent savings of $300-$900 million in externalities	-
(Wenzel et al., 2019)	Quantify VMT and energy use effects of ride-hailing due to deadheading (empty vehicle miles driven)	Analysis of driving data provided by a ride-hailing company in Austin, TX	-	Deadheading increases VMT: net effect on energy use is a 41–90% increase (compared to pre-service personal travel)	More efficient vehicle fleet is used, thus partially offsetting additional energy consumption	-	-	-	-	-
(Young and Farber, 2019)	Understand the consumer profile of ride-hailing users and whether this service substitute other travel modes in Toronto	Survey analysis	-	-	-	-	-	Ride-hailing does not impact public transit and car use, but there is a significant decrease in taxi ridership and a rise in active modes of travel in specific market segments	-	-
(de Souza Silva et al., 2018)	Analyzes socio-demographic and travel characteristics of ride-hailing demand in Brazilian cities	Statistical (regression) analysis	-	-	-	-	-	Majority of trips is replacing taxi and public transport	Safety and costs are the main determinants of use	"Leisure" trips are prevalent (due to zero tolerance law preventing drinking driving)
(Hall et al., 2018)	Estimate the effect of Uber on public transit ridership across U.S. metropolitan areas	Statistical (difference-in-differences regression) analysis	-	-	-	-	-	Uber is a complement for the average transit agency, increasing ridership by 5% after two years	Uber reduced commute times for public transit users while increasing congestion	-
(Rodier, 2018)	Analyze the effects of ride-hailing on auto ownership, VMT, and mode choice	Literature review	Modest reductions in auto ownership, varying due to studies' assumptions	New vehicle trips from ride-hailing availability: 8% to 22%; deadheading also increases VMT	-	-	-	Ride-hailing mostly substitutes than complements public transit	-	-
(Schwieterman and Smith, 2018)	Explore travel time and fare differences between UberPool and traditional transit service in Chicago, Illinois	Statistical (regression) analysis	-	-	-	-	-	-	Trip times are reduced by between 13.7% and 67.6%, depending on city area. Consumer savings range	Travel times on public transit and UberPool are similar for trips in which transit riders do not need to make

									between $.38/minute and $1.29/minute	transfers or walk long distances
(Vanderschuren and Baufeldt, 2018)	Estimate the potential for ridesharing in the developing world (case study: Cape Town) and its economic, social and environmental impacts	Literature review and survey analysis (multi-criteria analysis)	-	-	-	-	-	-	Provision of extra transportation option for the “mobility poor” and for those concerned about urban security	“Acceptability in the developed and the developing world is very different”
(Wu et al., 2018)	Evaluate ride-hailing’s impact on energy use and CO_2 emissions in China	Simulation (evaluation model)	-	-	-	Increased gasoline consumption led to additional 0.8 million tons of CO_2 emissions	-	43% of ride-hailing rides substituted private vehicles, while the remaining rides replaced other modes	-	-
(Yin et al., 2018)	Investigate the CO_2 emission reduction potential of ridesharing in the Paris region	Simulation (integrated transport-land-use model)	-	-	-	Decreases by 37 – 18%, depending on the scenario and time of the day analyzed	-	Ridesharing substitutes public transit and active modes	Road traffic decreases between 29 – 21%, congestion decreases between 20 – 5%, depending on the scenario and time of the day analyzed	Ridesharing leads to longer trip distances; emission reduction could have been greater if not for rebound effects
Autonomous vehicles (AVs)										
(Oh et al., 2021)	Investigate the network impacts of Automated Mobility-on-Demand (AMOD), including detailed models of AMOD fleet operations, in Singapore	Agent-based simulation model	-	Increase of 11.8–18.5% from baseline	-	CO_2 emissions are not calculated, although there is an increase in energy consumption (16.94 - 24.33% from baseline). Decrease of 4.3 - 5.7% in NOx and 5.6 - 8.2% in PM	-	-	More VKT lead to congestion (increase in travel delay up to 23%), while the journey time of those travelers who shifted from transit to AMOD can be significantly improved	-
(Alarfaj et al., 2020)	Examine the changes needed in vehicle electrification, electricity carbon intensity, and travel demand to meet reduction targets of 80% and higher for passenger vehicle transport in the USA by midcentury	Simulation model	-	-	-	To meet decarbonization targets of 80% or 90%, respectively, it is necessary to reduce the electricity generation carbon intensity to close to zero along with electrification of about 67% or 84% of vehicle travel	-	-	-	Degraded EV fuel economy due to automation would require higher levels of fleet electrification and/or further constrain the total vehicle travel allowable
(Brown and Dodder, 2019)	Analyze different effects of vehicle automation on energy efficiency and demand in the USA	Simulation (energy systems optimization model – MARKAL)	-	-	-	AV’s impacts on fuel prices could yield positive or negative impacts on emissions	-	-	AVs’ increasing travel demand may increase fuel use and petroleum-based fuel prices, while their efficiency improvements could reduce prices, which can increase or reduce the competitiveness of	-

									alternative-fueled vehicles, respectively	
(Gawron et al., 2019)	Study direct and indirect effects of electrified autonomous taxis (ATs) at the subsystem, vehicle, and mobility-system levels in Austin, TX	Simulation (Life cycle assessment (LCA) model)	-	-	-	Energy and GHG emissions are reduced by 60%. Further reductions of up to 87% can be achieved with electrical grid decarbonization, dynamic ride-share, longer vehicle lifetime, more energy efficient computer systems, and faster fuel efficiency improvements	-	-	-	-
(Gelauff et al., 2019)	Examine both the spatial and the welfare effects of AVs in two scenarios: car and public transit automation in the Netherlands	Simulation (general equilibrium model)	-	-	-	-	-	In full automation, shared AVs replace transit; longer commutes explain why bicycles are replaced	Increased due to reduction in generalized transportation costs, changes in modal split, relocation	-
(Jones and Leibowicz, 2019)	Explore the contributions of shared AVs (SAV) to climate change mitigation	Simulation (energy systems optimization model – OSeMOSYS) for Austin, TX	-	-	Effects are amplified when electric, more efficient vehicles are used	Reduced emissions (even in scenarios where VMT increase)	-	-	Shared AVs lower costs (even in scenarios where VMT increase)	Environmental and economic benefits of vehicle electrification are larger if electric SAV charging is optimally aligned with renewable electricity generation
(Kröger et al., 2019)	Model impacts of AVs on travel behavior in Germany and the USA	Simulation (diffusion model and an aspatial travel demand model)	-	Increase between 2.4 – 8.6% in Germany; 3.4 – 8.6% in the USA, depending on the scenario analyzed	-	-	-	AVs substitute public transport, whose share decreases between 3 – 11% in Germany and between 6 – 18% in the USA. Non-motorized modes' shares also fall. In Germany: 0.8 – 3.35%; USA: 2 – 6%	-	AV adoption might be higher in Germany (between 10% and 38%) than in the USA (between 8% and 29%)
(Liu et al., 2019)	Evaluate the effects of AV deployment on GHG emissions in China	Simulation (different scenarios of AV penetration rates and fuel consumption based on literature)	-	No significant change (assumptions too conservative)	Improved: between 0.4%-7.8%, depending on scenario	Depends on fuel consumption rates. AVs reduce emissions when they have better fuel economy and higher penetration rates	-	-	-	-
(Patella et al., 2019)	Analyze the carbon footprint of electric AV adoption in Rome	Simulation (Life cycle assessment (LCA) model and traffic simulation model)	-	VKT increases by 8% on highways and decreases for intra-urban roads (−5%)	-	AVs' lifetime GHG emissions are higher than other technologies' (35% higher than internal combustion	-	-	Total travel time decreases (−35% for intra-urban roads and −21% for highways), and average network speed increases (48% for intra-urban road	-

						engine vehicles, 22% higher than hybrid EVs, 5% higher than BEVs). 100% AV adoption leads to lower mobility system level emissions of about 60%			and 37% for highways)	
(Sethuraman et al., 2019)	Assess the impacts of electric AVs on energy consumption, ride comfort, travel time and infrastructure in Singapore	Simulation model	-	-	Energy savings of up to 9.3 % when the driving cycle is optimized, which can increase by 6.2% with platooning	-	-	-	-	The path width required for a micro-transit AV to turn 180 degrees is approximately 43% lower than for a standard urban bus
(Soteropoulos et al., 2019)	Review modelling studies investigating the impacts of AVs on travel behavior and land use	Literature review	Reduced, especially when shared AVs are considered	Most studies show increase in VMT/VKT; reduction when shared AVs are considered	-	-	-	Reduced public transport and slow modes share, especially from private AVs (some results show increase in walking/cycling)	AVs could lead to or curb urban sprawl, depending on assumptions on value of time, sharing and efficiency of other modes	Shared AVs could reduce the number of parking spaces
(Stogios et al., 2019)	Analyze the effects of AVs and vehicle electrification on GHG emissions	Simulation (traffic microsimulation and emission modeling)	-	-	-	In a high traffic situation, in either an expressway or urban corridor, aggressive AV driving reduces emissions by 26% and 3.44%, respectively, while cautious driving increases emissions by 35% and 19.62%	-	-	-	-
(Taiebat et al., 2019)	Forecast induced travel and energy rebound effects from AVs	Simulation (microeconomic model of VMT choice under income/time constraints, which is used to estimate elasticities with respect to fuel and time costs)	-	2–47% increase in travel demand for an average household. Net rise in energy use is a possibility, especially in higher income groups	-	-	-	-	Combined price elasticity of VMT demand is −0.4; demand is more elastic among the wealthy; households at all income levels are more sensitive to time costs than to fuel costs	-
(Venturini et al., 2019)	Assess the impact and effectiveness of transport policy measures in reaching emission reduction	Simulation (energy systems optimization model – TIMES-DK)	-	-	-	AVs lead to emissions reduction because other modes are cheaper and thus preferred; MaaS also reduces emissions because of higher vehicle occupancy rates	-	High car occupancy of MaaS generates a shift from bikes and buses towards cars	Market signals (taxes on CO2 and fossil fuels), have the highest impact to cut carbon emissions from transportation, while MaaS is the most cost-effective measure (more efficient use of transport due to	-

									higher occupancy rates)	
(Zhang et al., 2019)	Quantify AV's energy consumption and GHG emissions based on vehicle dynamics in a case study in NYC	Simulation (multiphysics energy model)	-	-	-	GHG emissions are 6.5% higher in an electric AV with a driver than in an AV without a driver	-	-	-	Ambient temperature and speed are the two main factors affecting energy consumption and GHG emissions
(Fox-Penner et al., 2018)	Project how electrification, sharing, and AVs will change transportation electricity demand and GHG emissions in the United States to 2050	Simulation (scenarios based on literature)	-	AVs increase VMT in both policy and stress case (high electricity use) scenarios, leading to more energy consumption	AVs are modelled as energy efficient (because of, for instance, platooning), thus decreasing energy intensity	56% emission reduction in policy case (EVs with AVs), going up to 80% in a decarbonized power sector. Scenario with AVs but no EVs has minimal GHG reduction	-	-	-	-
(Gawron et al., 2018)	Assess the contribution of CAV sensing and computing subsystems to vehicle life cycle energy use and GHG emissions	Simulation (Life cycle assessment (LCA) model)	-	-	-	CAV can increase energy use and GHG emissions by 3−20% due to increases in power consumption, weight, drag, and data transmission, but when use is optimized (e.g.: eco-driving, platooning, and intersection connectivity), there is a 9% reduction	-	-	-	-
(Hidaka and Shiga, 2018)	Estimate travel demand from AVs by forecasting growth on population and number of drivers	Simulation (human mobility and activity generation model)	-	-	-	-	-	Private AVs do not replace other modes; shared AVs replace all transportation modes but walking	Increased utility from multitasking in AVs, which contributes to modal share replacement	-
(Taiebat et al., 2018)	Examine AVs impacts on vehicle, transportation system, urban system, and society	Literature review	-	Higher vehicle utilization rate, more frequent and longer trips, deadheading result in greater VMT; fleet downsizing reduces VMT	Higher energy efficiency due to: optimal driving cycle, less idling, other driving functionalities; self-parking; rightsizing; platooning, etc.	-	Fewer crashes and less accident-related traffic	Integration or competition with mass transit; modal shift (e.g., rail/aviation to road travel)	Congestion increases due to induced travel; increased urban sprawl; job displacement and unemployment; reduced labor costs	Promotion of shared consumption; reduced need for parking infrastructure
(Vahidi and Sciarretta, 2018)	Assess the energy saving potential of CAVs based on first principles of motion, optimal control theory, and a review of the eco-driving literature	Literature review	-	-	Energy savings of up to: 3% from preview of static road information; 10% from traffic signals via Vehicle-to-Infrastructure	-	-	-	-	-

					(V2I) communication; 20% from reservation-based intersection control systems; 3% from anticipative car following; 7-10% from platooning for trucks; 20% from harmonizing impact of stop and go driving on traffic					
(Kockelman et al., 2017)	Analyze and understand the U.S. general public's perception towards AVs and their willingness of adoption	Survey analysis and simulation	Falls because less cars will be owned (the same vehicle drives itself to serve household members at different times/locations)	Increased VMT because opportunity cost of driving falls; underserved populations get access to mobility	-	-	More than 2,400 lives saved/year in Texas (at 90% market penetration)	-	Congestion falls because traffic becomes more efficient; freight costs fall because of avoided labor costs; billions in economic savings from avoided traffic accidents; increased productivity and leisure time	-
(Milakis et al., 2017)	Assess, from literature review, AVs' effects to policy and society, and identify areas for future research	Literature review	Shared AVs could replace between 67%-90% of conventional vehicles while delivering similar mobility levels	Increase in travel demand (between 3%-27%) due to longer trips, modal shift, underserved populations, deadheading. Impacts mitigated with shared AVs	Fuel savings between 31%-45%	AVs can lead to lower emissions of NOx, CO, and CO2, with higher positive impacts for shared AVs	Increased, especially at higher adoption rate; cyberattacks and other technical issues may be a risk	Modal shift from public transit, walking	Increase in costs (pricey new functionality); decrease in travel time	Increase in highway, intersection capacity; decrease in parking infrastructure (up to 90%)
(Ross and Guhathakurta, 2017)	Identify and quantify AVs' impacts on energy consumption	Simulation (scenarios based on literature)	-	Increased VMT from induced travel/new user groups, which increases energy use. Ridesharing offsets part of that.	-	-	-	-	-	-
(Stephens et al., 2016)	Estimate ranges of potential effects of AVs on VMT, fuel efficiency, and costs to consumers	Simulation	-	Increased VMT, but lower in scenario full AV/with ridesharing	More efficient in scenario full AV/with ridesharing	-	-	-	Decrease in costs to consumers due to savings on insurance, value of travel time	-