Texas A&M
Transportation
Institute

Technological Advancements in Transportation and Implications for Air Quality and Conformity

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1. INTRODUCTION

Currently, the transportation sector is facing revolutionary change, due to advances in technologies, and in how people travel and work. These changes linked to technological advancement are collectively expected to revolutionize transportation in the coming years, with implications for transportation planning and beyond. Often, these technological changes are discussed as "disruptive technologies" (*1*) or "transformational technologies and services" (*2*).

The advancements most relevant to the transportation sector include electric vehicles, shared mobility services, connected vehicles, and automated vehicles. These are often collectively defined as CASE vehicles (i.e. connected, automated, shared, and electric) by the automobile industry (*3*, *4*), or framed as "three revolutions" in transportation (*5*), where connected and automated vehicles are combined together. In this document, we use this categorization, namely 1) electric vehicles, 2) connected and automated vehicles, and 3) shared mobility. These are described briefly below:

<u>Electric vehicles (EVs):</u> These include hybrid, plug-in hybrid, and battery electric vehicles. They differ from conventional gasoline vehicles in that they obtain at least a part of the energy required for their propulsion from electricity. These vehicles have become more accessible to the public in recent years, as many new and affordable models have entered the market. Additionally, infrastructure to support the use of electric vehicles continues to grow, further increasing their popularity. According to MIT's Sloan Automotive Laboratory, 17 percent of new vehicles sold in the United States would be as plug-in EVs by 2050 (*6*).

<u>Connected and Automated Vehicles (CAVs):</u> Advances in the connected vehicle (CV) and automated vehicle (AV) technologies have the potential to change the way we travel through the creation of a safe, interdependent network that enables vehicles to interact with each other and with roadway infrastructure. According to the U.S. Department of Transportation (U.S. DOT), CAV technology is collectively expected to revolutionize transportation connectivity, in a manner analogous to the internet that revolutionized information technology advancements (*7*). According to a report by McKinsey (*8*) up to 15 percent of newly sold cars sold in 2030 could be fully autonomous pending solving the regulatory and technological issues around CAVs.

Shared Mobility (SM): Shared mobility is a transportation service that is shared among users on an as-needed basis. The most common are transportation network companies (TNCs) for ridesharing such as Lyft or Uber, but SM also encompasses a variety of services including public transit, carsharing, bike sharing (dockless mobility bikes and scooters), shuttle services and microtransit, and other modes. While public transit emerged around two centuries ago connecting people between major origin and destination locations, carsharing and bike sharing in recent years have allowed people to share trips between any locations.

Each of these technologies has potential impacts on the transportation sector, though uncertainties remain in terms of regulations and market factors that will affect their adoption. The purpose of this report is to synthesize how these advancements in the transportation sector can affect emissions, and air quality, and implications for transportation conformity. Previous studies conducted by TTI on this subject addressed electric vehicles and automated and connected vehicles, respectively (*9*, *10*). This report provides an expanded review of studies that reflect newer literature and findings, and the implications for air quality and conformity in Texas. This report is organized as follows: Sections 2,3, and 4 describe the key findings from literature on the emissions and air quality impacts of electric vehicles, connected automated vehicles and shared mobility respectively. Section 5 provides conclusions and discusses potential implications.

2. EMISSIONS AND AIR QUALITY IMPACTS OF ELECTRIC VEHICLES

2.1 EV TECHNOLOGY

As mentioned in the introductory section, EVs obtain at least a part of the energy required for their operation from electricity. The term EV is used to refer to three main types of automotive drivetrains, hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and battery electric vehicles (BEVs). HEVs have a two-part drive system, a conventional fuel engine deriving energy from fuel and an electric drive deriving energy secondarily from the alternator or regenerative braking. PHEVs are like HEVs but derive their energy mostly from electricity and can engage the fuel engine as needed. BEVs are fully electric and derive their energy solely from onboard high capacity battery packs. Currently, several EV models are available in the market from various manufacturers. The availability of affordable EVs, along with the increasing availability of charging infrastructure, has contributed to their popularity in recent years.

2.2 FACTORS AFFECTING EV EMISSIONS IMPACTS

There are four main factors to consider when evaluating the emissions impact of EVs, as shown in Figure 1, and described briefly below.

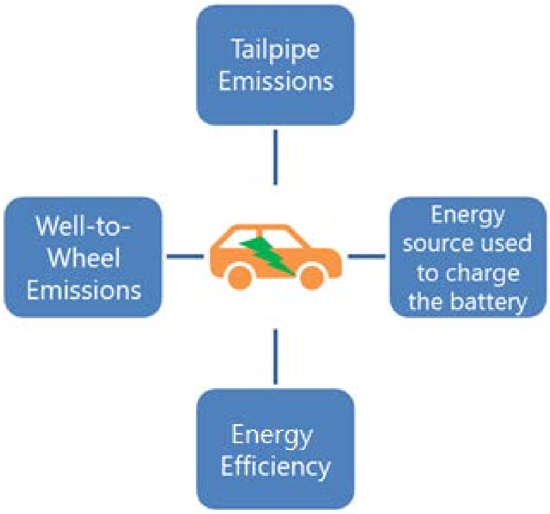

Figure 1. Factors to Consider while Assessing Emissions of EVs.

Tailpipe Emissions: EVs running solely on electricity do not emit any direct tailpipe emissions, compared to conventional gasoline vehicles. This aspect is most relevant from a transportation conformity perspective, where the operational emissions of the vehicle (i.e. emissions from the transportation network) are most important.

Well-to-Wheel (WTW) Emissions: WTW emissions, unlike tailpipe emissions, also take into consideration emissions associated with the "upstream" elements of the energy production process. The WTW emissions for electric vehicles include emissions produced during electricity generation, processing and distribution. Thus, the source of energy to power the EVs has an impact on the overall WTW emissions. For example, for plug-in electric vehicles (PHEVs, and BEVs), the energy and emissions associated with the electricity needed to charge the vehicle batteries have to be considered. The majority of energy for EVs comes from traditional sources based on coal or natural gas. An emerging way to offset the energy demand is the integration of renewable energy systems (such as wind, solar etc.) to charge an EV battery, which can promote the further reduction of pollutant emissions (*11*). A study showed that when the source of electricity for EVs is from coal, emissions of SO_2 increased by 3-10 times and doubled for NO_x compared to gasoline-powered vehicles (*12*). Figure 2 shows a comparison of electricity sources in Texas against national averages, along with emissions by vehicle type on a WTW basis. Although there are differences in terms of the electricity sources between Texas and the US as a whole, the overall emissions seem to be consistent with the national averages.

Energy Efficiency: Energy efficiency refers to the amount of energy utilized to drive a vehicle and is directly proportional to the amount of CO_2 emissions. EVs have an energy efficiency of about 59 to 62% of the total energy derived from the grid to the wheels. This is much greater than that of the conventional gasoline vehicles with an energy efficiency ranging between 17 to 21% (*11*).. Thus, compared to conventional vehicles, EVs utilizes much less energy and thereby produces less CO_2 emissions to drive the same amount compared to conventional vehicles.

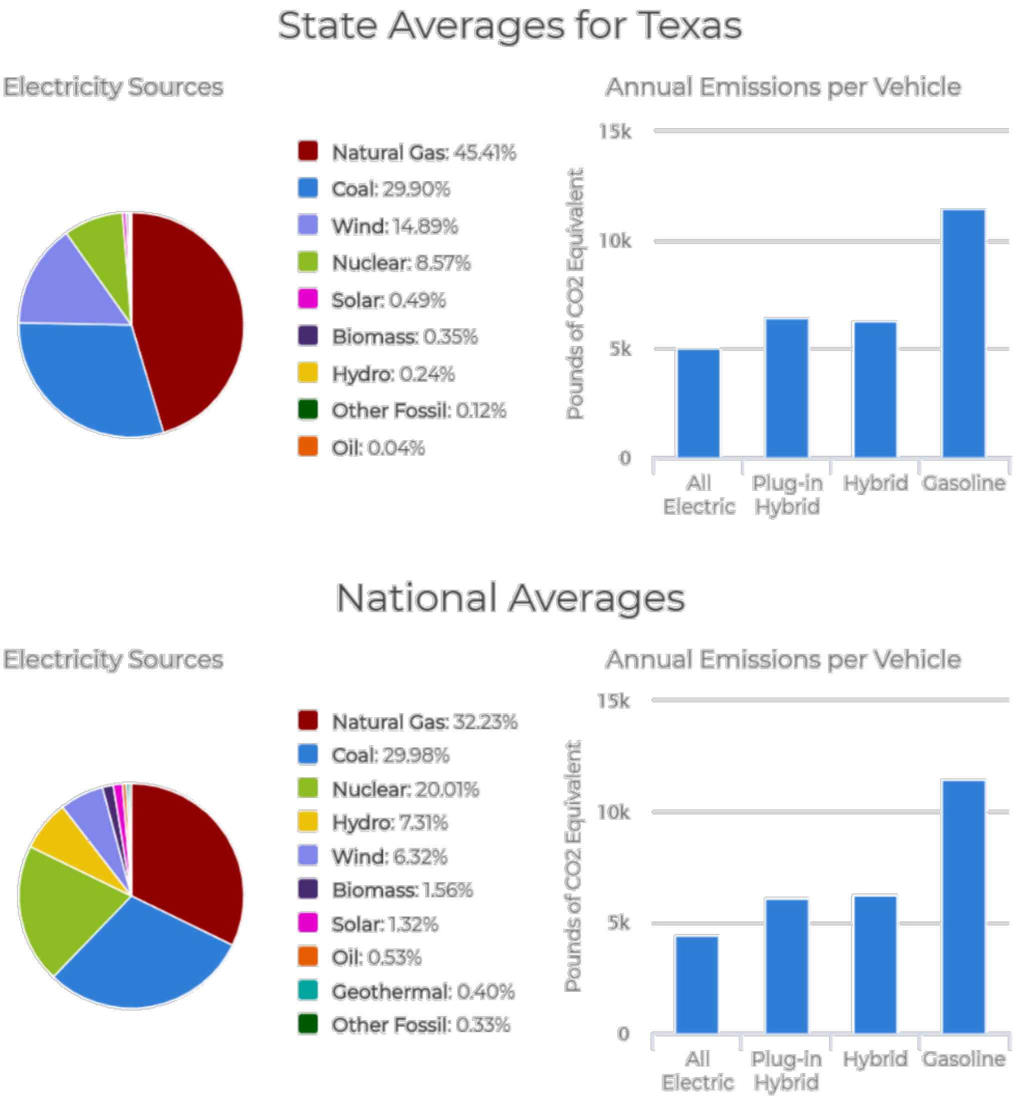

Figure 2. Comparison of Texas Average with National Averages on EVs emissions (*11*)**.**

2.3 FINDINGS FROM LITERATURE

A recent study developed a high-level overview of the relationship between EVs and the environment, considered all factors as discussed above (*13*). The study developed a conceptual methodology (shown in Figure 3), capturing the complex relationship between the type of EV, and transportation related air pollution. The Figure 3 highlights the emission chain framework for EVs consisting of the manufacturing process, energy sources, electricity generation, tailpipe emissions, pollutant emissions, human health impacts, climate change and quality of life. The amount and the type of processes from which emissions are released depend on the type of EV. While HEVs are primarily powered by gasoline with small batteries supporting the combustion engine, PHEVs are powered by both gasoline and electricity, and BEVs are solely by electricity. If the electricity is derived from non-renewable sources (such as coal, or oil), the energy generation is found to produce air pollutants and GHGs emissions affecting human health, quality of people's lives and climate change. Using the conceptual methodology shown in Figure 3, the study also quantified the emissions impacts of EVs categorized by the type of EVs and pollutants (criteria pollutant and GHGs). The scale displayed in Figure 4 is based on quantitative analysis of 65 research articles classifying the emission benefits on a scale of 1-3 where 1 represents zero benefits in reducing emissions, 2 medium benefits and 3 high benefits.

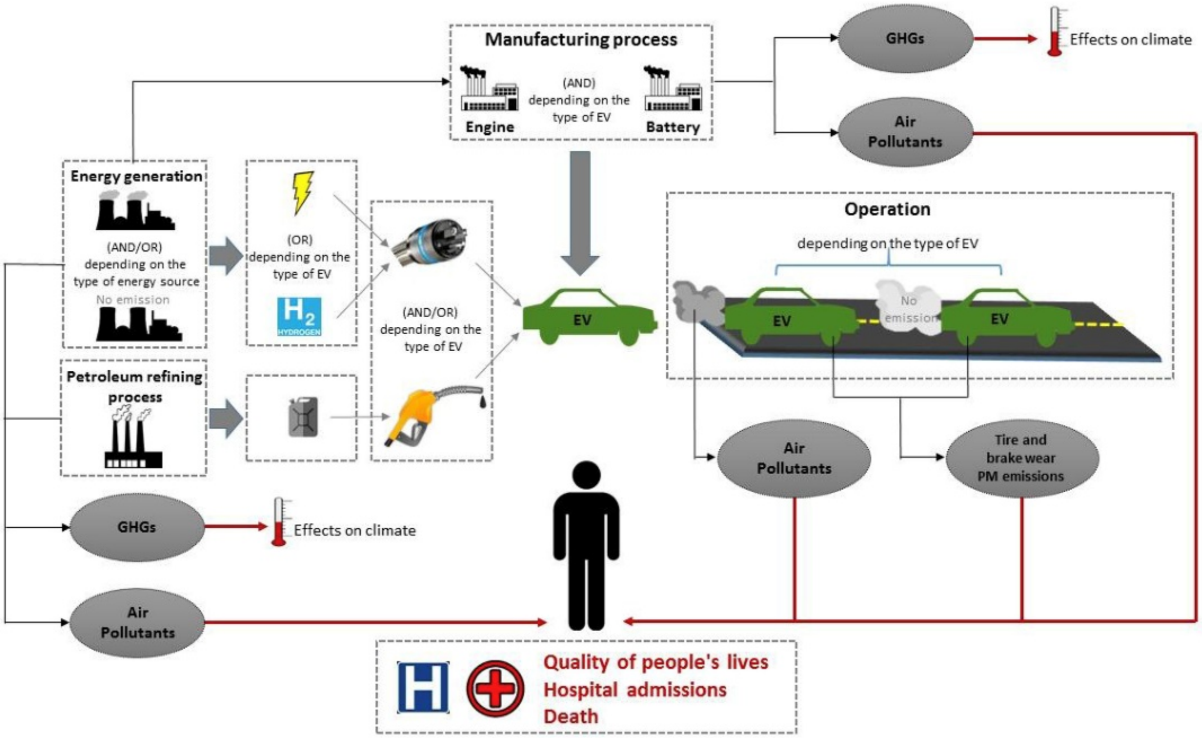

Figure 3. Emission Impacts of Electric Vehicles (*13*)**.**

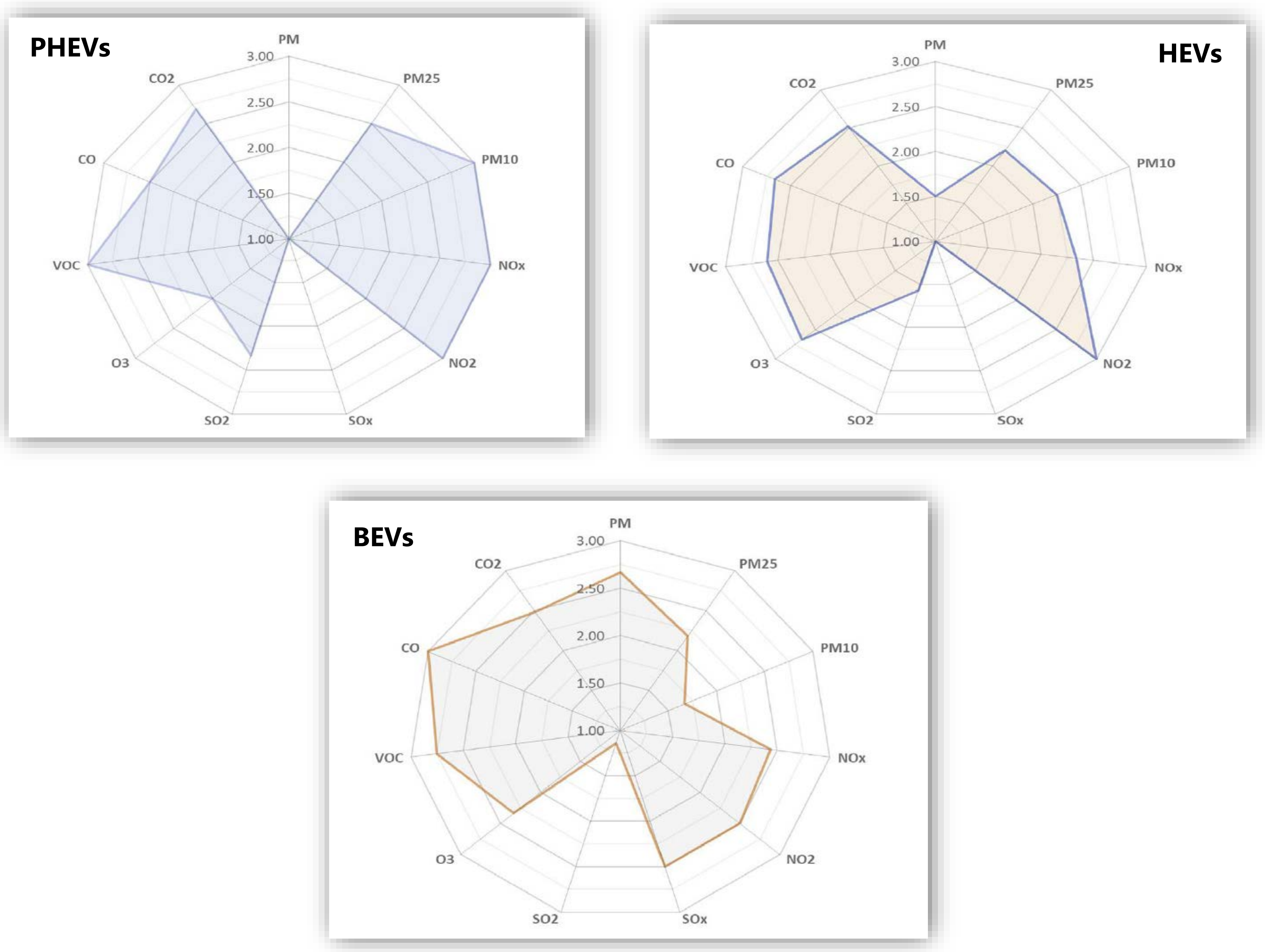

Figure 4. Quantitative analysis of average air pollutants by type of EVs (*13*).

Further findings from various studies on the emissions impacts of EVs are described below:

Criteria Pollutant Emissions

Particulate Matter (PM): With respect to particulate matter (PM), the analysis showed an only moderate reduction in PM emissions on average. The greatest benefits were obtained from HEVs due to the lower life-cycle emissions associated with HEVs compared to BEVs and PHEVs that have a high percentage of energy generated from coal-based power plants. Studies have shown that greater the energy generation from coal to power EVs, greater the negative impacts of EVs on air quality (*14*, *15*). One way to offset the negative impact is to depend on renewable sources of energy to charge EVs. With renewable energy sources, studies also have pointed out that the main source of PM emissions would be from non-exhaust emissions (brake and tire wear) depending on the vehicle weight (*16*, *17*).

Oxides of Nitrogen (NOx), Volatile Organic Compounds (VOCs), and Carbon Monoxide (CO): Studies showed the highest overall emission reductions from EVs over conventional vehicles for NO_x, VOCs and CO. Studies pointed out that emissions from an electricity generation component have an insignificant effect on these pollutants irrespective of the source of energy used for powering the EVs *(23, 24)*. Studies have found no significant emission impact for SO_2 from EVs (*18*, *19*).

Ozone: Studies found ozone emission benefits to be mixed as a result of EVs depending on the spatial variability and atmospheric conditions (*20*, *21*). This could be attributed to ozone being a secondary pollutant formed as a result of a chemical reactions between NOx and VOCs in the presence of sunlight. The formation of ground-level ozone is a function of season, time of day/sunlight intensity, location of the source, and atmospheric conditions.

Other Pollutants

Studies have found a significant reduction in CO_2 emissions with EVs in comparison to conventional gasoline vehicles. Compared to PM, CO_2 are found to be less sensitive to the energy source type used to power EVs (*14*, *15*).

Table 1 summarizes key findings from various studies in further detail.

Table 1. Literature Synthesis on Emissions and Air quality Impacts of EVs.

Reference	Country	EV Type	Effect	Additional Notes
			Criteria Pollutants	
Weis et al (2016) (22)	U.S.	PEVs & BEVs	Lower life cycle PM emissions	Authors found the time of charging is important to reduce PM emissions.
Huo et al (2015) (23)	U.S.	BEVs	Increased PM emissions by 30%.	Scenario with increasing the share of coal-fired power plants and the introduction of BEVs in California could increase PM emissions by 30%.
Huo et al (2013) (14)	China	BEVs	WTW PM_{10} emissions increased by 360% and $PM_{2.5}$ by 250%	Analysis was based on wheel-to-well emissions. Results are found to vary depending on the energy grid.
Ke et al (2017) (24)	China	EVs	Scenario found $PM_{2.5}$ on-road emissions to reduce by 29% and increase coal power plant emissions by 2.4% resulting in a total reduction of 0.2%	Scenario with 20% of private light-duty passenger vehicles and 80% of commercial passenger vehicles electrified.
Soret et al (2014) (25)	Spain	EVs	Decreased PM_{10} emissions by 3-4% mainly due to the high impact of non-exhaust emissions	Three fleet electrification scenarios considered corresponding to 13, 26 and 40% of fleet.
Brinkman et al (2010) (26)	U.S.	PHEVs	Reduced on-road NOx emissions by 27 tons per day (16%) and increased power plants NOx by 3 tons per day (2%)	Aggressive scenario with 100% of PHEVs in the vehicle fleet. Energy mix consisted of majority of natural gas.
Colella et al (2005) (27)	U.S.	Fuel cell EVs (FCEV)	Reduced CO emissions by 52%	Study considered the introduction of FCEVs using hydrogen produced in coal power plants.
Nichols et al (2015) (19)	U.S.	PHEVs	Reduced emissions of NOx (54%) and CO (96%) but increased life-cycle emissions of SO_2 from 0.0077 g/mile to 0.72 g/mile	Study conducted in Texas and considered the 2012 electricity grid in Texas (~50% from natural gas, 25% from coal, 25% renewable and nuclear).
Brinkman et al (2010) (26)	U.S.	PHEVs	Reduced O_3 by 2–3 ppb, NO_x by 27 tons per day from a fleet of 1.7 million vehicles and VOCs by 57 tons per day and increased NOx by 3 tons per day from power plants	Study considered 100% PHEV penetration.

Reference	Country	EV Type	Effect	Additional Notes
Razeghi et al (2016) (20)	U.S.	PHEVs and BEVs	Reduced 8-h-averaged ozone by 6 ppb and 24-h-averaged $PM_{2.5}$ by 6 mg/m3	Decrease in emissions was observed by incorporating wind energy in the electricity grid and charging at off-peak hours.
Huo et al (2010) (14)	China	BEVs	WTW NOx decreased by 120% and SO_2 decreased by 370%	Analysis was based on wheel-to-well emissions. Results are found to vary depending on the energy grid.
Ke et al (2017) (24)	China	EVs	EV1: Reduced NO_X by 8.1% in total and increased SO_2 by 1.1% on road EV2: Reduced NO_X by 10% in total and increased SO_2 by 3.5% on road	Scenario EV1 with 20% of private light-duty passenger vehicles and 80% of commercial passenger vehicles electrified. EV2 with all private light-duty passenger vehicles electrified.
Ferrero et al (2016) (28)	Italy	EVs	Tailpipe on-road emissions of NO_2 reduced by 5.5% and NO_X reduced by 14.1%	Scenario considering 50% of light vehicles replaced by EVs.
Soret et al (2014) (25)	Spain	PHEVs and BEVs	Insignificant impact of EV charging on NO_2 ($<3\ \mu g/m^3$) but found to reduce NO_X by 11-17%	Low emission impacts are attributed to the energy mix. Renewable energy sources represented 33% and nuclear energy 21% of the energy generation profile.
Li et al (2016) (29)	Taiwan	EVs	Reduced on-road emissions of CO by 85%, VOC by 79%, and NOx by 27%	Scenario considering replacement of all light-duty vehicles with EVs.
Vidhi et al (2018) (30)	India	EVs	Reduced NO_X by 7-25%, CO by 85% if charging energy from renewables and increased SO_2 by 11% if charging energy from fossil fuels	100% EVs by 2030.
Other Pollutants				
Doucette et al (2011) (31)	U.S France China India	BEVs	Varying levels of GHGs depending on the energy mix	An increase in GHGs was observed in countries with high CO_2 intensity power generation such as India and China. Significant reduction in GHGs can be observed only when the power generation become less CO_2 intensive.
Huo et al	China	BEVs	WTW CO_2 emissions reduced by 20%	Analysis was based on wheel-to-well emissions.

Reference	Country	EV Type	Effect	Additional Notes
(2013) (14)				Results are found to vary depending on the energy grid.
Moro et al (2016) (32)	Europe	EVs	GHGs reduced by 50-60% from EVs compared to diesel or gasoline operated vehicles	Well-To-Wheels (WTW) calculations, and results are found to vary depending on the energy source. Predominantly renewable sources of energy are used to power EVs.
Teixeira et al (2018) (33)	Brazil	EVs	GHGs reduced by 10-12 times compared to engine powered vehicle fleet	Study also found substitution of 25-100% of taxi fleet by EVs could reduce 1000-5600tons of CO_2/year.

3. EMISSIONS AND AIR QUALITY IMPACTS OF CONNECTED AUTOMATED VEHICLES (CAVS)

3.1 CAV TECHNOLOGY

AVs are defined by the U.S. National Highway Traffic Safety Administration (NHTSA) as "those in which operation of the vehicle occurs without direct driver input to control the steering, acceleration, and braking and are designed so that the driver is not expected to constantly monitor the roadway while operating in self-driving mode." NHTSA recently adopted the Society of Automotive Engineers International (SAE) definitions for different levels of automation (*34*). The SAE definitions divide vehicles into levels based on "who does what, when". CV technology, on the other hand refers to the ability for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication. CV technology is an important input to realizing the full potential benefits and broad-scale implementation of the highest level of automation (*7*). These two technologies may converge or diverge from each other based largely on developments in the private sectors (e.g., vehicle manufacturers, third-party vendors). While some sectors envision full automation that does not require inter-vehicle and infrastructure communication, others see synergies between the two technologies (*35*). As many of the technologies between AVs and CVs overlap, they are often collectively discussed under the CAV umbrella. Figure 5 graphically represents the evolution of CVs to AVs.

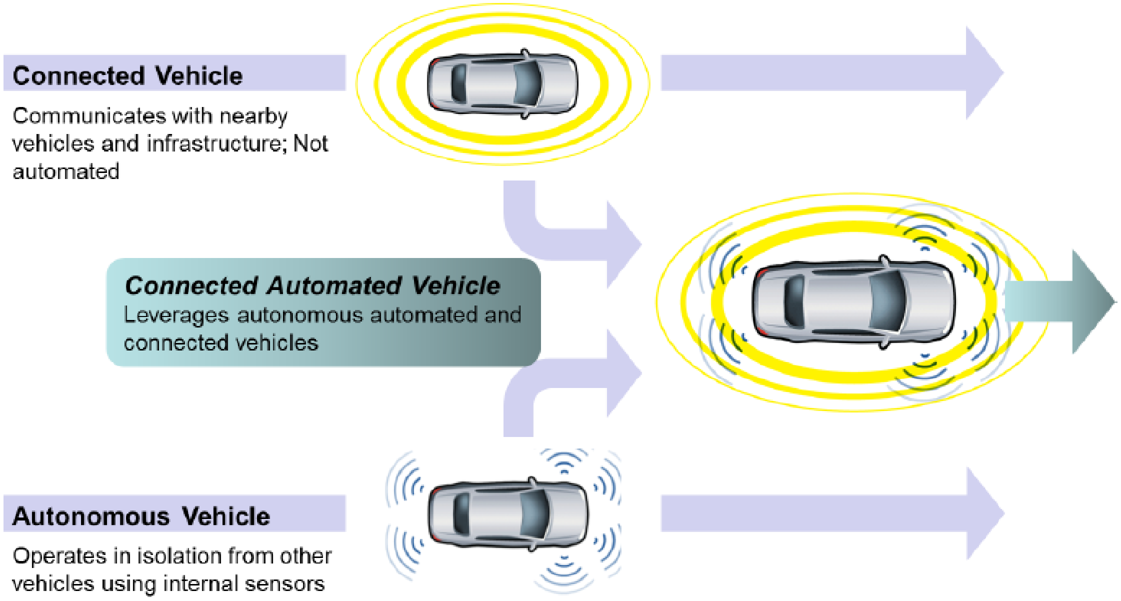

Figure 5. Evolution of Connected to Automated Vehicles (*7*)**.**

3.2 FACTORS AFFECTING CAV EMISSIONS IMPACTS

There have been several studies that identified how CAV technology could influence the current transportation system in terms of vehicle operations, vehicle design, traffic flow, travel access, vehicle ownership, and land use patterns. These studies have noted substantial energy and emission effects through more efficient traffic flows, vehicle platooning, and light-weight design, optimizing routing, and shared ridership schemes. Furthermore, CAVs are found to be more responsive to alternative vehicle technologies compared to conventional vehicles, which results in additional emission reduction (*36*). On the other hand, studies have also pointed out possibilities of changes in travel demand due to the productive use of in-vehicle time, shared ridership, reduced driver burden, and travel access for the disabled, young, and older adults. These changes in travel demand could have the opposite effect on the energy and emissions effects received through efficient traffic and routing mechanisms. Therefore, the energy and emissions impacts of CAV technology (Figure 6) are dependent on the interaction between the following mechanisms:

- Fuel efficiency
- Changes in travel demand
- Synergies with alternative vehicle technology

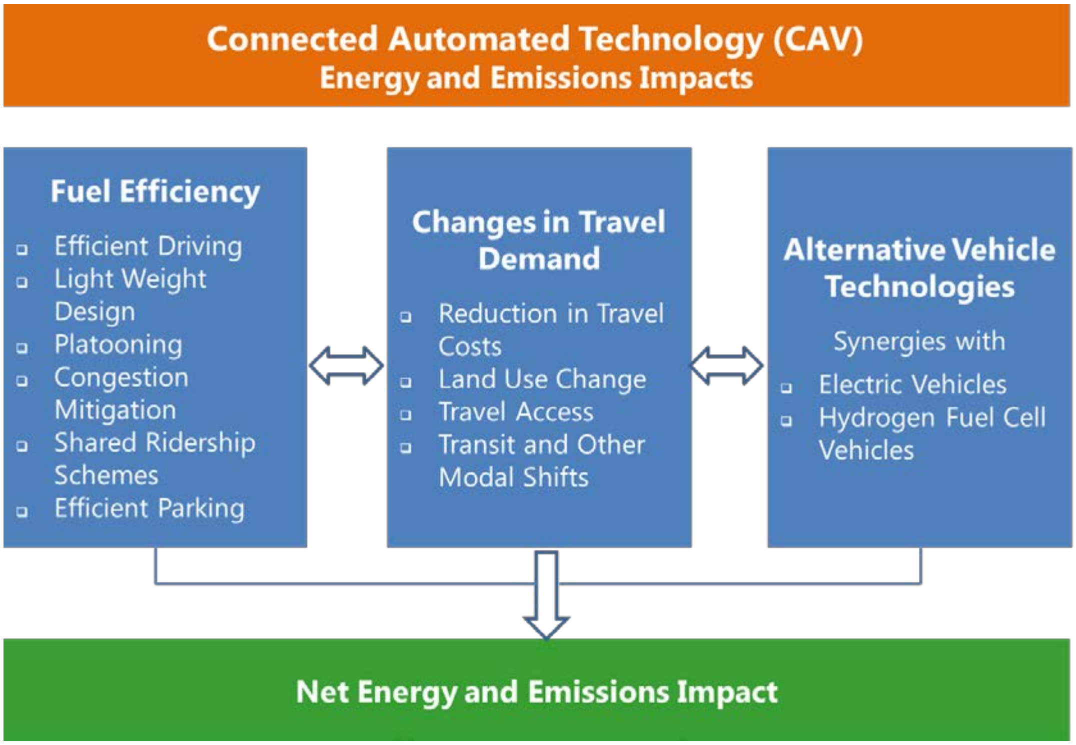

Figure 6. Framework for Assessing Energy and Emissions Impacts of CAVs.

3.3 FINDINGS FROM LITERATURE

Table 2 provides a summary of findings from the literature. It contains a compilation of findings regarding the energy and emissions effects from different studies. Metrics that studies have employed to quantify the environmental impacts include fuel savings and energy consumption, travel demand, travel time, and total emissions (mostly related to carbon dioxide emissions). While some studies have relied on real world testing to quantify the impacts, a few other studies have based their results on model simulations or from travel and survey studies. Additional notes are provided in the table as relevant. Studies mentioned in Table 2 address many of the CAV mechanisms in isolation, and their impacts on energy demand or emissions are often specific to the conditions being considered. To date, a limited number of studies have analyzed the combined effects of CAV technology by considering all factors of fuel efficiency, travel demand, and synergy with alternative fuel technology. Researchers from the National Renewable Energy Laboratory projected the effect of different categories on emission reduction (*37*). Figure 7 highlights the potential of CAVs to result in large fuel savings and use intensity depending upon the extent of incorporation and interaction between different factors. Combining all the categories (fuel, use, and energy intensity), this study illustrates that

CAV technology would likely result in greater travel demand, but travel would be efficient, and potentially coupled with alternative fuel technology.

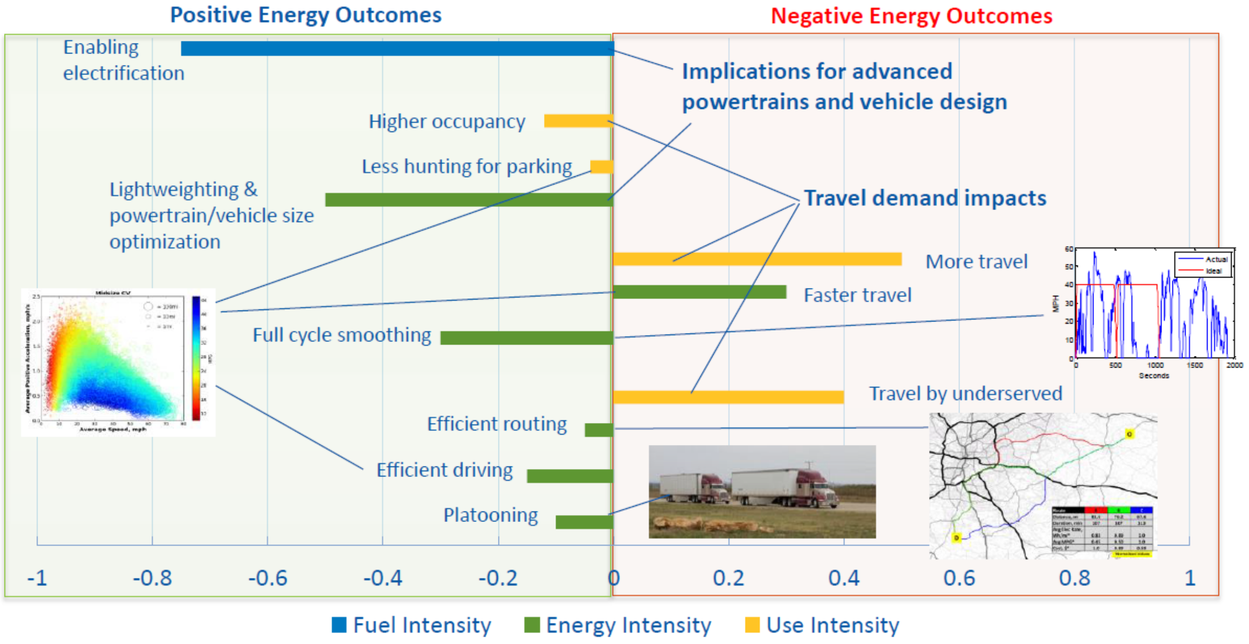

Figure 7. Overall Environmental Impacts (*37*).

Table 2. Literature Synthesis on Emissions and Air quality Impacts of CAVs.

References	Country	Effect	Potential Effect	Additional Notes
Fuel Efficiency Effects				
Barth et al (2013) (*38*)	U.S.	Efficient Driving: eco-driving, smooth start stop, stop elimination	Emission reduction: 12 percent of CO_2, 37 percent of NOx, 41 percent of HC, 48 percent of CO Fuel consumption savings of 13 percent Travel time increase of 6 percent	Simulation results compared with real-world experiments in Southern California for passenger vehicles.
Guo et al (2013) (*39*)	U.S.		13 percent reduction of CO emissions due to eco-routing 8 percent increase in travel time	Integrated TRANSIMS – MOVES framework was used to evaluate real world Greater Buffalo–Niagara Region transportation network considering passenger cars and single-unit short-haul diesel trucks.
ERTICO (2018) (*40*)	Europe		20 percent decrease in CO_2 emissions 20 percent decrease in fuel consumption	Simulation modeling results from testing the application of intelligent transportation systems (ITS) strategies in Europe.
Anderson et al (2016) (*41*)	U.S.	Light Weight Design	20-25 percent weight reduction by 2030 and 32-50 percent by 2050 10 percent reduction in weight results in 6-7 percent reduction in fuel consumption	Based on National Research Council and EPA (*42*) estimates.
Caltrans (2014) (*43*)	U.S.	Platooning: running vehicles together for a closer headway that reduces the air drag resistance	12–18 percent reduction in fuel consumption	Partial Automation for Truck Platooning project tested automated truck platoons on a closed track in 2003.
Lu and Shladover (2014) (*44*)	U.S.		4–14 percent reduction in fuel consumption	Fuel use savings of 4 percent, 10 percent, and 14 percent was estimated for the first, second, and third trucks, respectively, in a three-truck platoon with six meter spacing.
Mackenzie et al	U.S.		10–25 percent reduction in energy	Combining the estimates reported by (*46*, *47*) for

References	Country	Effect	Potential Effect	Additional Notes
(2014) (45)			consumption	heavy trucks for the entire United States.
RITA (2011) (48)	U.S.		10–20 percent reduction in fuel consumption	Field testing of freight trucks by AERIS research project
Tsugawa (2013) (49)	Japan		10 percent reduction in energy consumption	10 percent reduction in energy consumption was found for a three-truck platoon at 80 km/h, with a 20m gap between trucks.
Clifford et al (1997) (50)	U.S.	Congestion Mitigation	8–13 percent increase in traffic speed 23–39 percent increase in fuel efficiency	The authors estimate an increase in traffic speed and fuel efficiency for all vehicles to vary depending upon the level of V2V communication and extent of traffic smoothing algorithms implementation.
Clifford (2012) (51)	U.S.		2 percent reduction in fuel consumption today that increases to 4 percent in 2050	The authors developed their estimates by combining estimates on annual volume of fuel wasted due to congestion (*52*) and total fuel consumption (*53*) for vehicle travel (light-duty and heavy-duty).
Fagnant and Kockelman (2014) (54)	U.S.	Shared Ridership Schemes	A single shared CAV could replace nine to 13 vehicles in an urban scenario. No change in travel demand	Based on using an agent-based model for assigning vehicles around a region in combination with National Household Travel Survey (NHTS) data indicate that a single shared AV could replace between nine and 13 privately owned or household-owned vehicles, without compromising current travel patterns.
Mackenzie et al (2014) (45)	U.S.		20 percent reduction of CO_2 emissions	Assumption based on a study that estimated a reduction of 8.8 percent of GHG emissions through car-sharing in North America based on surveys.
Brown et al (2013) (55)	U.S.		12 percent reduction in VMT	Assumption based on user surveys and focus groups to study the effects of dynamic ridesharing among single occupancy vehicles.
Brown et al	U.S.	Efficient Parking	4 percent reduction in VMT	Assumption based on an estimate by (*52*) that 19

References	Country	Effect	Potential Effect	Additional Notes
(2013) (55)				gallons of fuel per person per year is wasted in looking for parking
Changes in Travel Demand				
Mackenzie et al (2014) (45)	U.S.	Reduction in Travel Costs	4–156 percent increase in travel demand	Combined published vehicle travel elasticity estimates and present day vehicle running and fixed costs with estimates on reduction in travel costs from switching to CAV. Travel demand increase ranging from 4 percent for low level automation to 156 percent for level 4 automation for light duty vehicles.
Brown and Gonder (2014) (37)	U.S.	Land Use Changes	Decrease in travel cost Increase in urban sprawl Decrease in the need for parking spaces	Qualitative estimates
Brown and Gonder (2014) (56)	U.S.	Travel Access for underserved population (youth, disabled, and elderly)	40 percent increase in travel demand	Based on data from the 2009 National Highway Transportation Survey (*57*) and the 2003 Freedom to Travel study (*58*) for the entire United States
Synergies with Alternative Vehicle Technologies				
Fulton et al (2017) (59)	U.S.	Integration with EV, and SM	80 percent reduction in GHGs emissions by 2050	Scenario was modeled based on a base year of 2015. Projected year is a multi-modal scenario consisting of widespread vehicle electrification and automation, maximizing the use of shared vehicle trips.

4. EMISSIONS AND AIR QUALITY IMPACTS OF SHARED MOBILITY

4.1 SHARED MOBILITY TECHNOLOGY

Shared mobility (SM) has experienced tremendous growth in recent years and combined with advances made in bluetooth and wireless technologies have made these services accessible and efficient. The different types of shared mobility include bikesharing, carsharing, flexible commercial delivery, public transit, ridesharing, ride-hailing, scooter sharing, shuttles, and taxis and limos. For example in New York from 2015 to 2018, privately hired vehicles that mostly relate to shared mobility services like Uber and Lyft have increased by more than 300% where as the traditional taxi services has seen a steady reduction in number as shown in Figure 8 (*60*). Key advantages of these new services include addressing the first and last mile issues, reduce traffic congestion and transportation costs, reduce air pollution, and improve efficiency and accessibility (*61*).

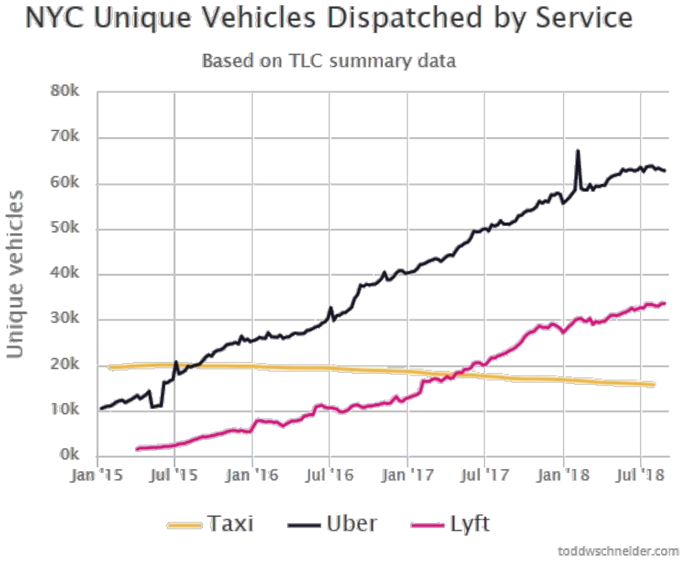

Figure 8. Increase in ride-sharing vehicles in New York from 2015 to 2018 (*62*)**.**

4.2 FACTORS AFFECTING SM EMISSIONS IMPACTS

SM has the potential to reduce congestion, emissions and air quality in urban areas by reducing car ownership. One study, for example, estimated replacement rates as high as 15:1 (i.e., 15 private car owners can be replaced by a shared mobility vehicle) (*60*). But this number may not be realistic as it assumes that all the shared mobility vehicles are carpooling with full capacity. In addition, this number also did not account for existing public transportation service in major cities, where shared mobility services can actually increase cars on the road by diverting users off public transit. The emissions and air quality impacts of SM technology (Figure 10) are dependent on the classification of the modal shift and integration with emerging technologies.

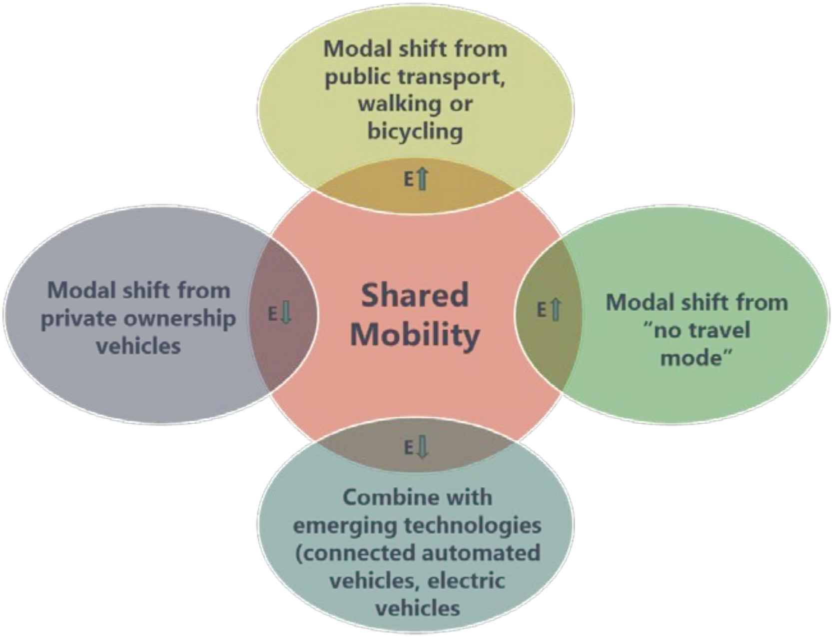

Figure 9. Emissions (E) Impacts of Shared Mobility Strategies.

To assess impacts, it is necessary to understand the use of SM in the context of actions that would otherwise occur in its absence. This could result in four types of impacts:

1. <u>Modal shift from private ownership vehicles</u>: a car-owning household may join carsharing rather than acquire an additional car which would result in shifting emissions from a private vehicle to a shared vehicle. A study by Martin et al, found a removal of 9 to 13 vehicles from the road for every roundtrip carsharing based on an online survey (*63*). The same study translated the vehicle removal (based on vehicle sales) into emissions and found an average GHGs reduction of 34 to 41 percent per household. Similar estimates were found in a study conducted in Europe where SM is found to reduce GHGs by 40 to 50 percent at an individual level (*64*). Factors that

motivate people to use SM compared to their private vehicle are parking availability, cost and convenience (*65*).

2. Modal shift from "no travel" mode: SM may provide opportunities for people to make trips that wouldn't have otherwise occurred. Households with no vehicle access may join carsharing, resulting in an increase in travel activity and thereby emissions (*66*). A recent study based on online survey found out that shared mobility has an 8 percent induced travel effect (*67*).
3. Modal shift from transit, bicycling and walking: Public transportation trips, biking or walking trips, when transferred to the shared mobility trips and may cause an increase in congestion, emissions, and reduced air quality. A recent study in New York indicates the reduction in the number of bus and subway trips due to SM services as shown in Figure 10 (*68*). Another study found the difference in emissions to be neutral or negative resulting from transit modal shift (*69*). The study based on an online survey found for every 10 people shifting from transit, 9 took it more.

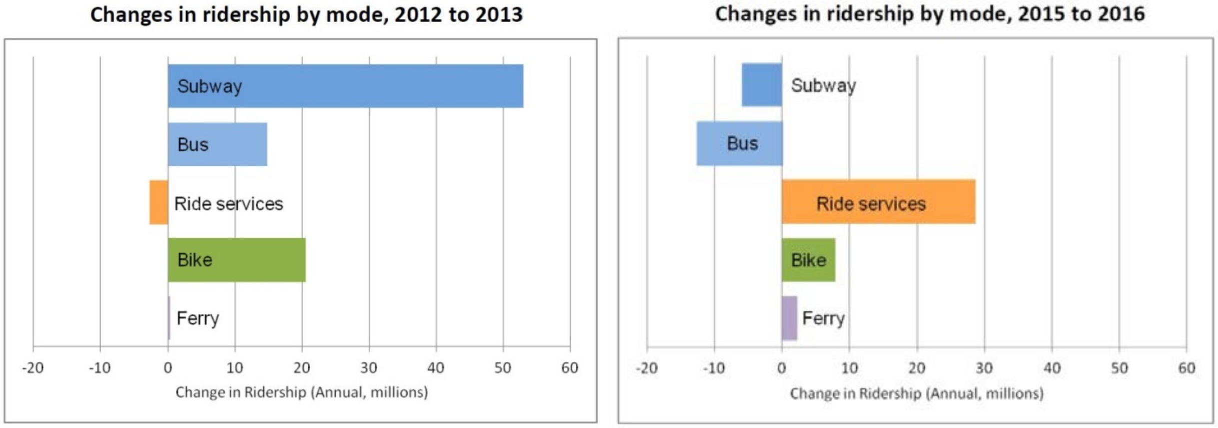

Figure 10. Modal shift in traffic after the introduction of shared mobility services in New York (*68*)**.**

4. Synergy with alternative technologies: Studies have shown a promising way to offset the increase in emissions is to integrate the SM with other emerging technologies with cleaner fuels (*66*). Therefore, evaluating the impact of SM on air quality requires a more integrated system approach incorporating the model shift and integration with other emerging technologies.

4.3 FINDINGS FROM LITERATURE

Table 3 summarizes studies which have evaluated air quality and emission impacts of SM services.

Table 3. Literature Synthesis on Emissions, and Air quality Impacts of Shared Mobility Strategies.

Study	Country	Effect	Additional Notes
		Criteria Pollutants	
Fagnant et al (2014) (54)	U.S.	Shared autonomous vehicles (SAV) reduces PM_{10} by 6.5%	SAVs replace around eleven conventional vehicles but adds up to 10% more travel distance. Overall emission benefits are due to the fleet-efficiency changes.
Vasconcelos *et al (2017)* (70)	Portugal	The PM emissions increased by 36 kg for cars running on gasoline and diesel. But decreased by 42 kg in case the vehicles are electric or hybrid.	Increase in emissions is attributed to increase in the usage of motorized vehicles by people who were previously walking, cycling, or using public transport. This increase can be offset when the SM is combined with cleaner technologies.
Ma et al (2018) (71)	China	Reduces $PM_{2.5}$ by 12.8 tons per year in Beijing–Tianjin–Hebei (BTH) region	Ridesharing trips mainly shift from private ownership vehicles.
Fagnant et al (2014) (54)	U.S.	Shared autonomous vehicles (SAV) reduces: - SO_2 by 19% - CO by 34% - NO_x by 18% VOC by 49%	The emission reduction are mainly due to the reduction of personal vehicle ownership in the city with introduction of shared mobility services.
Vasconcelos et al (2017) (70)	Portugal	Overall environmental cost of all gaseous emissions is positive only when the SM vehicles are electrified and not with other fuels	Car sharing system introduce a demand in motorized vehicle mode, transferring some trips from non-motorized modes (walking or cycling) and public transport.
Ma et al (2018) (71)	China	Reduces: • SO2 by 48 tons per year • NOx by 262 tons per year	Ridesharing trips mainly shift from private ownership vehicles.
		Other Pollutants	
Chen et al (2016) (72)	U.S.	Reduces individual transport-related energy use and GHG emissions by 51%. Saves 5% in household transport-related energy use and GHG emissions	Quantifies life-cycle reductions in energy use and GHG emissions as a result of adoption of carsharing in US.
Martin and Shaheen (2011) (73)	U.S.	Reduces GHG by 0.58 metric tons per year per household on observed impact, based on vehicles sold	Online survey with members of major carsharing organizations (6281 individuals). Observed impact is based on vehicles sold.

Study	Country	Effect	Additional Notes
Fagnant et al (2014) (54)	U.S.	Shared autonomous vehicles (SAV) reduces GHG by 5.6%	Emission improvements were observed only when the SM was integrated with CAVs.
Minnet and Pearce (2011) (74)	U.S.	Reduces GHG emission by 4100-8200 tons per year through casual carpooling in San Francisco	Saves $US 30.0 million per year, including conserving 1.7–3.5 million liters (0.45–0.9 million US gallons) of fuel.
Chen et al (2016) (72)	U.S.	Saves 3% in household transport-related energy use and GHG emissions considering rebound effect	Calculated the direct rebound effect and estimated the indirect rebound effect as a range.
Martin and Shaheen (2011) (73)	U.S.	Reduces GHG by 0.84 metric tons per year per household as a full impact	Full impact is based on vehicles sold and postponed purchases combined.
Vasconcelos et al (2017) (70)	Portugal	GHG emissions increased by 1136 tons for cars running on gasoline and by 1085 tons for cars running on diesel. However, decreased by 1186 tons in case the vehicles are electric or hybrid.	The GHG emissions increased when fossil fuels are used. Improved vehicle technology like electric or connected vehicles can improve the overall emission impact. Overall, there is a modal shift from public transport to the road.
Nurhadi et al (2017) (75)	Sweden	Carsharing over short to medium distances reduces GHG emissions by 20–40%	Electric vehicles are the most competitive among Biogas, Ethanol, Gasoline, Plug-in Hybrid, and Electric vehicles.
Dowlatabadi and Namazu (2015) (76)	Canada	Reduces GHG emissions by more than 30%	Although, there is an overall GHG emission reduction, VMT across the system increased marginally.
Liimatainen et al (2018) (77)	Finland	Estimates a reduction of 8.7 million tons GHG by year 2050 for the proposed ride sharing activity	The change in public behavior is important to achieve this emission reduction and will need stringent policy measures like limiting parking spaces of private cars.
Firnkorn and Muller (2011) (78)	Germany	Reduces GHG emissions by 238 kg per year	A survey of 256 individuals on using SM service car2go.

5. IMPLICATIONS FOR AIR QUALITY AND CONFORMITY

This section provides a discussion of the potential effects of the three transportation disruptors/technological advancements on air quality and their potential implications for regulatory air quality and conformity analyses.

5.1 CONFORMITY

The Clean Air Act (CAA) defines EPA's responsibilities for protecting public health and improving the nation's air quality (*79*). The CAA requires EPA to set limits on the amount of certain pollutants, called criteria pollutants, allowed in the air. When the level of any of these pollutants exceeds the standard in an area, EPA designates that area as being in nonattainment (NA) for that pollutant. After an area is designated as an NA area by EPA, the state is required to develop a State Implementation Plan (SIP) for the area to implement, maintain, and enforce to reduce the pollutant level in the NA area down to equal or lower than the standard(s) (*80*).

In transportation planning, the primary concern is with on-road mobile source emissions, which are enforced through the transportation conformity process. Conformity provisions vary depending on the pollutant and nonattainment status (i.e. whether a nonattainment [NA] or maintenance area), but commonly, areas have an on-road mobile source emissions goal in the SIP termed as the motor vehicle emissions budget, which represents a cap on emissions from on-road mobile sources. NA and attainment maintenance areas must demonstrate that emissions resulting from future actions, as identified by the transportation planning and programming process and documented in the metropolitan transportation plans and transportation improvement programs, will not exceed the area's emissions budget. This task is achieved through a process known as demonstrating transportation conformity, which must be conducted periodically, i.e., within two years of the initial budget and every four years thereafter, if the plan is updated, or if the SIP changes. If conformity cannot be demonstrated by a specified deadline, or if the plan expires before a new one is adopted, the area enters into a conformity lapse. For areas in a conformity lapse, federal transportation funds cannot be spent on capacity-enhancing projects, though certain safety, transit, and air quality projects may go forward.

5.2 IMPLICATIONS OF TECHNOLOGICAL ADVANCEMENTS FOR AIR QUALITY AND CONFORMITY

The Figure 11 gives an overview of the factors to be considered for the different disruptors in the context of conformity and regional air quality analyses. The red arrows in Figure 11 represent the factors contributing to the increase in emissions and the green arrows indicate factors that could reduce emissions. These factors, along with additional considerations on emissions and air quality impacts are discussed below.

Electric Vehicles

Several factors have to be considered in terms implications for emissions, overall air quality levels and policy implications.

- Tailpipe Emissions: Considering only tailpipe emissions, EVs have considerably lower emissions than conventional vehicles. PHEVs and BEVs do not produce tailpipe emissions when they are in electric mode, and hence the expected increase in the number of these vehicles in the future means that there will potentially be a notable reduction of mobile source emissions captured in a conformity determination emissions inventory.
- Well-to-Wheel Emissions: When the overall WTW emissions are taken into consideration, however, the positive emissions benefits depend on the type of EV and energy source used. Although PHEVs and BEVs have no tailpipe emissions, they extract more energy generated by power plants, unlike HEVs. These plants are considered point sources, along with other sources such as chemical plants, refineries, electric utility plants, and other industrial sites. Hence, reduction in mobile source emissions from these vehicles may not necessarily lead to better regional air quality because emissions generated for charging EVs are not accounted for in transportation air quality conformity determinations. It is important to note that in a broader air quality perspective, it is essential to take into consideration the emissions from electricity generation when accounting for EVs' impacts on overall air quality levels and doing so may have broader future policy implications.
- Environmental Justice: Another factor to consider is the location of emissions associated with EVs. An increasing number of EVs can cause a shift in tailpipe emissions (more in the urban areas) to power generation emissions from power plants (located more commonly in rural areas). The extent of reduced emissions

from the urban area translating into increased emissions in the rural areas must be considered in the context of environmental justice in the regulatory processes.

Shared Mobility

The impact of SM on emissions and air quality depends on two main factors:

- Modal shift: SM is found to increase or decrease emissions depending on the mode replaced:
    - Replace transit, bicycle and walking trips, or creating new trips: SM is found to result in higher emissions when it replaces walking, biking or transit trips, or in creating trips that may not have otherwise occurred.
    - Replacing personal vehicle trips: SM can reduce private vehicle ownership, and may potentially contribute to reduced trips, vehicle miles traveled and emissions.
- Integration with cleaner emerging technologies: synergies with low-emissions cleaner fuel technologies such as CAVs and EVs can result in additional reduction in emissions and overall air quality.

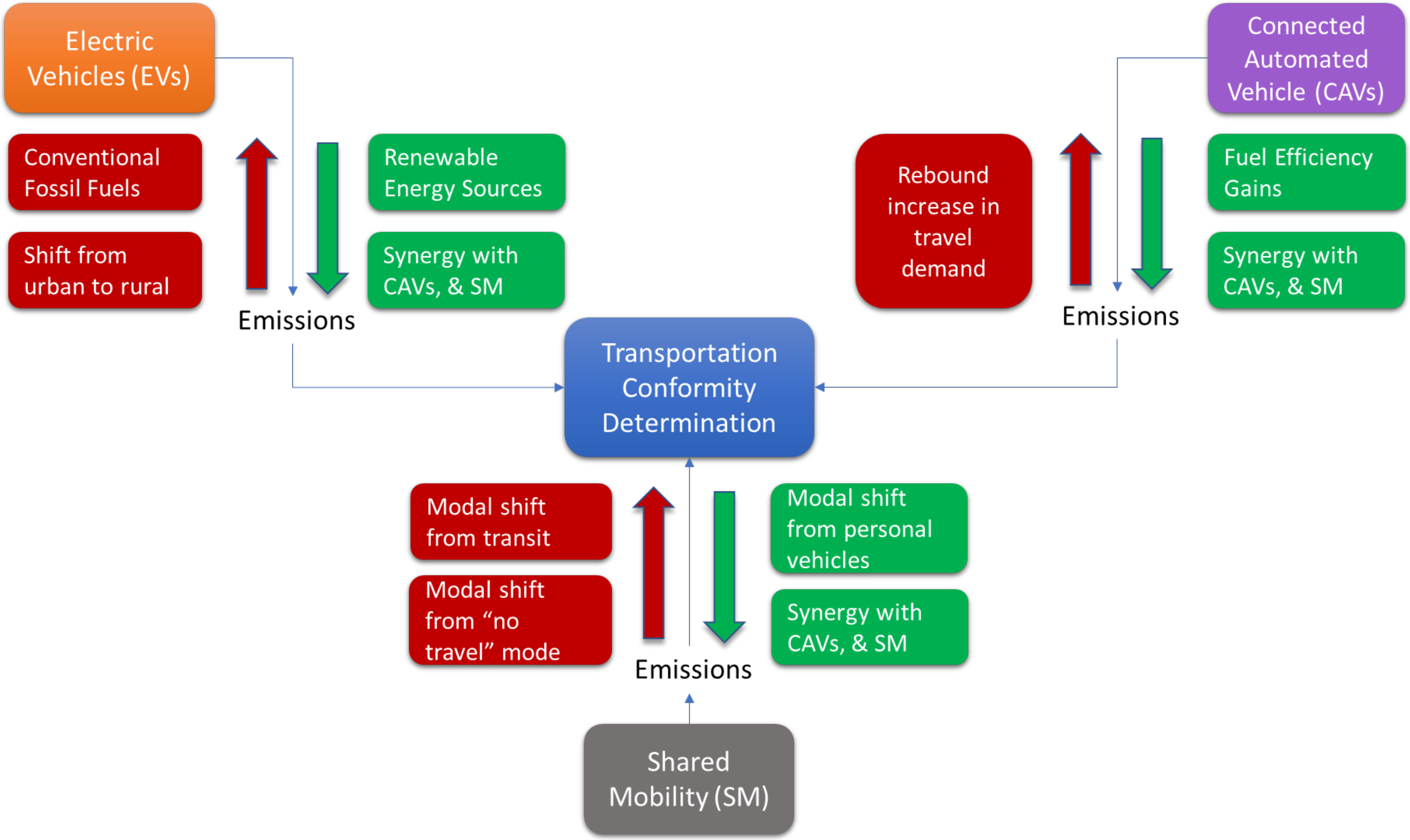

Figure 11. Implications of Disruptors for Air Quality and Conformity.

Connected Automated Vehicles (CAVs)

The impact of CAVs on fuel use and emissions is a function of four factors that are interdependent

- The fuel efficiency of CAVs: there are a variety of ways in which CAVs could increase fuel efficiency, like reducing vehicle weight, vehicles operating more efficiently, and motorists choosing to share rather than own vehicles. The fuel efficiency gains translate into reduced total emissions.
- The total change in vehicle travel resulting from CAVs: Several studies analyzing the issue of change in existing travel behaviors and patterns found that travel demand is likely to increase. The increase is attributed to the reductions in travel costs, increases in the number of travelers, and increases in urban sprawl. This increase leads to increase in travel activity thereby increasing emissions.
- Possible synergy with alternative vehicle technologies: A promising way to achieve positive emission benefits is to integrate the CAV technology with alternative fuel technologies (renewable sources of energy) so the two technologies could complement each other. Given that most automobile manufacturers in the United States are currently oriented towards conventional gasoline-powered vehicles, dramatic technological, policy, economic, and societal changes would likely be required for the majority of CAVs to operate on alternative fuels.
- Policies: Studies also point out that a way to balance out the increase in travel demand is to have policies in place that promote scenarios that mitigate possible travel demand increases and encourage the adoption of CAVs that benefit multiple users (such as shared mobility). Policies should be oriented toward using CAVs to achieve overall travel system optimization such as efficient and integrated corridor management, environmental travel information (*81*).

The possibility of emission benefits would occur only when the emission reduction gains through enhanced fuel economy and alternative fuels backed by policies outweigh the rebound effect caused by an increase in travel demand.

5.3 STRATEGIES DEVELOPED TO HELP STATE AGENCIES TO INCORPORATE EMERGING TECHNOLOGIES

This section briefly discusses strategies developed to help state agencies incorporate emerging technologies into their planning and policy making. A primer for state and local decision makers was developed by Transportation Research Board (TRB) for strategies to advance CAVs in policymaking (*82*). The primer developed strategies for policymakers to help align transportation agency goals with CAVs technologies. Specific to air quality, strategies to mitigate increased VMT and emissions are as follows:

- Subsidize shared AV use
- Implement transit benefits
- Implement a parking cash-out strategy
- Provide for location-efficient mortgages to encourage shared AV use
- Implement land-use policies and parking requirements
- Apply road-use pricing

In terms of travel behavior, the National Cooperative Highway Research Program (NCHRP) produced a Guidebook to help state departments of transportation and metropolitan planning organizations to account for CAVs in their planning and modeling activities (*83*). The Guidebook developed a framework with new planning and modeling process to help agencies to incorporate CAVs in the transportation environment. The framework (Figure 12) consisted of five key elements. The first three elements, (1) Data, (2) Planning Context, (3) Modeling corresponds to the traditional forecasting which consists of collecting data, planning by setting goals and performance metrics and modeling with the data and goals to assess transportation scenarios. The new two elements added in the context of the CAV technology correspond to the adoption timeline and communicating uncertainty. With the rapid proliferation of the CAVs, the Guidebook suggests a balance to be made between the level of adoption/advancement of CAV technology with the rate of adoption over the planning time period. The fifth element indicates that uncertainty must be included along with the model results to help decision makers interpret the results in the proper context.

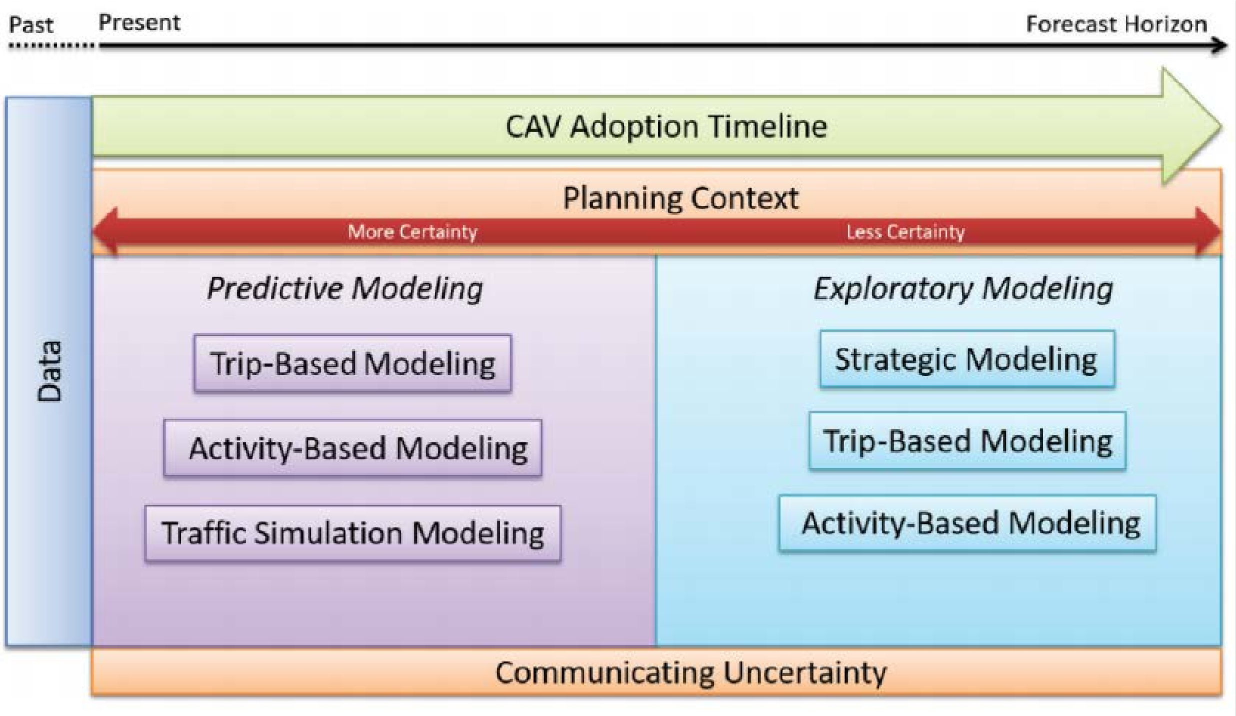

Figure 12. Framework for CAV Planning and Modeling (*83*)**.**

5.4 SUMMARY

The increase in EVs, CAVs and SM options will have a direct impact on vehicle tailpipe emissions. But, the proliferation of these technologies also has broader impacts and implications on local and regional air quality. An extensive body of literature on the emissions and air quality impacts of electric vehicles, connected automated vehicles and shared mobility was conducted and discussed in this report. The report also discusses potential implications for regulatory air quality processes, and emerging tools developed to help state and federal agencies to incorporate these disruptors into their planning process. This review can help TxDOT and its partner agencies understand the effect of these different factors, scenarios and penetration levels to help plan for future fleet changes and potential impact on air quality in nonattainment and maintenance areas.

REFERENCES

1. Trey, R., Baker, J. Wagner, M. Miller, G. Pritchard, and M. Manser. Disruptive Technologies and Transportation. 2016.
2. Transportation Research Board. Critical Issues in Transportation 2018. Transportation Research Board, Washington, D.C., 2018.
3. Mercedes Benz. Future Mobility: The Revolution of CASE. https://www.mercedes-benz.com/en/mercedes-benz/innovation/future-mobility-revolution-CASE/. Accessed Apr. 25, 2019.
4. Daimler. CASE – Intuitive Mobility | Daimler. https://www.daimler.com/case/en/. Accessed Apr. 25, 2019.
5. Sperling, D., and A. Brown. Three Revolutions : Steering Automated, Shared, and Electric Vehicles to a Better Future.
6. Massachusetts Institute of Technology Sloan Automotive Laboratory. On the Road toward 2050: Report Massachusetts Institute of Technology Potential for Substantial Reductions in Light-Duty Vehicle Energy Use and Greenhouse Gas Emissions. 2015.
7. USDOT. Connected and Automated Vehicles. 2018.
8. McKinsey & Company. Automotive Revolution-Perspective towards 2030. 2015.
9. Farzaneh, R., Y. Chen, J. Johnson, J. Zietsman, C. Gu, T. Ramani, L. D. White, M. Kenney, and Y. Zhang. Accounting for Electric Vehicles in Air Quality Conformity - Final Report. 2014.
10. Farzaneh, R., S. Vallamsundar, and T. Ramani. Air Quality Issues Related to Alternative Modes and Fuels Emissions and Air Quality Impacts of Connected and Automated Vehicle Technology. 2015.
11. Department of Energy. Alternative Fuels Data Center: Emissions from Hybrid and Plug-In Electric Vehicles. https://afdc.energy.gov/vehicles/electric_emissions.html. Accessed Mar. 5, 2019.
12. Huo, H., Q. Zhang, M. Q. Wang, D. G. Streets, and K. He. Environmental Implication of Electric Vehicles in China. Environmental Science & Technology, Vol. 44, No. 13, 2010, pp. 4856–4861. https://doi.org/10.1021/es100520c.
13. Requia, W. J., M. Mohamed, C. D. Higgins, A. Arain, and M. Ferguson. How Clean Are Electric Vehicles? Evidence-Based Review of the Effects of Electric Mobility on Air Pollutants, Greenhouse Gas Emissions and Human Health. Atmospheric Environment, Vol. 185, No. April, 2018, pp. 64–77. https://doi.org/10.1016/j.atmosenv.2018.04.040.
14. Huo, H., Q. Zhang, F. Liu, and K. He. Climate and Environmental Effects of Electric Vehicles versus Compressed Natural Gas Vehicles in China: A Life-Cycle Analysis at Provincial Level. Environmental Science and Technology, Vol. 47, No. 3, 2013, pp. 1711–1718. https://doi.org/10.1021/es303352x.

15. Kantor, I., M. W. Fowler, A. Hajimiragha, and A. Elkamel. Air Quality and Environmental Impacts of Alternative Vehicle Technologies in Ontario, Canada. International Journal of Hydrogen Energy, Vol. 35, No. 10, 2010, pp. 5145–5153. https://doi.org/10.1016/j.ijhydene.2009.08.071.
16. Simons, A. Road Transport: New Life Cycle Inventories for Fossil-Fuelled Passenger Cars and Non-Exhaust Emissions in Ecoinvent V3. International Journal of Life Cycle Assessment, Vol. 21, No. 9, 2016, pp. 1299–1313. https://doi.org/10.1007/s11367-013-0642-9.
17. Timmers, V. R. J. H., and P. A. J. Achten. Non-Exhaust PM Emissions from Electric Vehicles. Atmospheric Environment, Vol. 134, 2016, pp. 10–17. https://doi.org/10.1016/j.atmosenv.2016.03.017.
18. Wu, Y., and L. Zhang. Can the Development of Electric Vehicles Reduce the Emission of Air Pollutants and Greenhouse Gases in Developing Countries? Transportation Research Part D: Transport and Environment, Vol. 51, No. 2017, 2017, pp. 129–145. https://doi.org/10.1016/j.trd.2016.12.007.
19. Nichols, B. G., K. M. Kockelman, and M. Reiter. Air Quality Impacts of Electric Vehicle Adoption in Texas. Transportation Research Part D: Transport and Environment, Vol. 34, 2015, pp. 208–218. https://doi.org/10.1016/j.trd.2014.10.016.
20. Razeghi, G., M. Carreras-Sospedra, T. Brown, J. Brouwer, D. Dabdub, and S. Samuelsen. Episodic Air Quality Impacts of Plug-in Electric Vehicles. Atmospheric Environment, Vol. 137, 2016, pp. 90–100. https://doi.org/10.1016/j.atmosenv.2016.04.031.
21. Nopmongcol, U., J. Grant, E. Knipping, M. Alexander, R. Schurhoff, D. Young, J. Jung, T. Shah, and G. Yarwood. Air Quality Impacts of Electrifying Vehicles and Equipment Across the United States. Environmental Science and Technology, Vol. 51, No. 5, 2017, pp. 2830–2837. https://doi.org/10.1021/acs.est.6b04868.
22. Weis, A., P. Jaramillo, and J. Michalek. Consequential Life Cycle Air Emissions Externalities for Plug-in Electric Vehicles in the PJM Interconnection. Environmental Research Letters, Vol. 11, No. 2, 2016, p. 024009. https://doi.org/10.1088/1748-9326/11/2/024009.
23. Huo, H., H. Cai, Q. Zhang, F. Liu, and K. He. Life-Cycle Assessment of Greenhouse Gas and Air Emissions of Electric Vehicles: A Comparison between China and the U.S. Atmospheric Environment, Vol. 108, 2015, pp. 107–116. https://doi.org/10.1016/j.atmosenv.2015.02.073.
24. Ke, W., S. Zhang, Y. Wu, B. Zhao, S. Wang, and J. Hao. Assessing the Future Vehicle Fleet Electrification: The Impacts on Regional and Urban Air Quality. Environmental Science and Technology, Vol. 51, No. 2, 2017, pp. 1007–1016. https://doi.org/10.1021/acs.est.6b04253.
25. Soret, A., M. Guevara, and J. M. Baldasano. The Potential Impacts of Electric Vehicles on Air Quality in the Urban Areas of Barcelona and Madrid (Spain).

Atmospheric Environment, Vol. 99, 2014, pp. 51–63. https://doi.org/10.1016/J.ATMOSENV.2014.09.048.

26. Brinkman, G. L., P. Denholm, M. P. Hannigan, and J. B. Milford. Effects of Plug-in Hybrid Electric Vehicles on Ozone Concentrations in Colorado. Environmental Science and Technology, Vol. 44, No. 16, 2010, pp. 6256–6262. https://doi.org/10.1021/es101076c.
27. Colella, W. G., M. Z. Jacobson, and D. M. Golden. Switching to a U.S. Hydrogen Fuel Cell Vehicle Fleet: The Resultant Change in Emissions, Energy Use, and Greenhouse Gases. Journal of Power Sources, Vol. 150, No. 1–2, 2005, pp. 150–181. https://doi.org/10.1016/j.jpowsour.2005.05.092.
28. Ferrero, E., S. Alessandrini, and A. Balanzino. Impact of the Electric Vehicles on the Air Pollution from a Highway. Applied Energy, Vol. 169, No. x, 2016, pp. 450–459. https://doi.org/10.1016/j.apenergy.2016.01.098.
29. Li, N., J. P. Chen, I. C. Tsai, Q. He, S. Y. Chi, Y. C. Lin, and T. M. Fu. Potential Impacts of Electric Vehicles on Air Quality in Taiwan. Science of the Total Environment, Vol. 566–567, 2016, pp. 919–928. https://doi.org/10.1016/j.scitotenv.2016.05.105.
30. Vidhi, R., and P. Shrivastava. A Review of Electric Vehicle Lifecycle Emissions and Policy Recommendations to Increase EV Penetration in India. Energies, Vol. 11, No. 3, 2018, pp. 1–15. https://doi.org/10.3390/en11030483.
31. Doucette, R. T., and M. D. McCulloch. Modeling the CO2 Emissions from Battery Electric Vehicles given the Power Generation Mixes of Different Countries. Energy Policy, Vol. 39, No. 2, 2011, pp. 803–811. https://doi.org/10.1016/j.enpol.2010.10.054.
32. Moro, A., and L. Lonza. Electricity Carbon Intensity in European Member States: Impacts on GHG Emissions of Electric Vehicles. Transportation Research Part D: Transport and Environment, Vol. 64, No. November 2016, 2018, pp. 5–14. https://doi.org/10.1016/j.trd.2017.07.012.
33. Teixeira, A. C. R., and J. R. Sodré. Impacts of Replacement of Engine Powered Vehicles by Electric Vehicles on Energy Consumption and CO2 Emissions. Transportation Research Part D: Transport and Environment, Vol. 59, No. February, 2018, pp. 375–384. https://doi.org/10.1016/j.trd.2018.01.004.
34. National Highway Safety Traffic Administration. Federal Automated Vehicles Policy Accelerating the Next Revolution In Roadway Safety. 2016.
35. Transportation Research Board. Workshop on the Future of Road Vehicle Automation. http://www.trb.org/Main/Blurbs/168539.aspx.
36. Underwood, S. E., S. Marshall, and J. Niles. Automated, Connected, and Electric Vehicles An Assessment of Emerging Transportation Technologies and a Policy Roadmap for More Sustainable Transportation A Report for the The Connected Vehicle Proving Center (CVPC) at the University of Michigan-Dearborn. 2014.
37. Brown, A., and J. Gonder. An Analysis of Possible Energy Impacts of Automated

Vehicles. 2014.

38. Barth, M., K. Boriboonsomsin, and G. Wu. The Potential Role of Vehicle Automation in Reducing Traffic-Related Energy and Emissions. 2013.
39. Guo, L., S. Huang, and A. W. Sadek. An Evaluation of Environmental Benefits of Time-Dependent Green Routing in the Greater Buffalo–Niagara Region. Journal of Intelligent Transportation Systems, Vol. 17, No. 1, 2013, pp. 18–30.
40. ERTICO ITS Europe. ECoMove Kicks Off! https://ertico.com/ecomove-kicks-off/. Accessed Mar. 5, 2019.
41. Anderson, J., N. Kalra, K. Stanley, P. Sorensen, C. Samaras, and O. Oluwatola. Autonomous Vehicle Technology: A Guide for Policymakers. RAND Corporation, 2016.
42. USEPA. INVENTORY OF U.S. GREENHOUSE GAS EMISSIONS AND SINKS: 1990 – 2010. Washington, DC, 2011.
43. California Department of Transportation. Caltrans Interests in Connected/Automated Vehicles. 2014.
44. Lu, X.-Y., and S. E. Shladover. Automated Truck Platoon Control and Field Test, Springer, Cham, pp. 247–261.
45. Don MacKenzie, Z. Wadud, and Paul Leiby. A FIRST ORDER ESTIMATE OF ENERGY IMPACTS OF AUTOMATED VEHICLES IN THE UNITED STATES. 2014.
46. Tsugawa, S. Energy and Environmental Implications of Automated Truck Platooning within Energy ITS Project. 2013.
47. Lu, X., and S. E. Shladover. Automated Truck Platoon Control and Field Test. 2013.
48. Research and Innovative Technology Administration. Study of ITS Applications for the Environment. Navigation Systems with Eco-Routing Features Can Improve Fuel Economy by 15 Percent. 2011.
49. Tsugawa, S. Final Report on an Automated Truck Platoon within Energy ITS Project International Task Force on Vehicle Highway Automation 17th Annual Meeting. 2013.
50. CLIFFORD, M. J., R. Clarke, S. B. RIFFAT, and Elsevier. DRIVERS' EXPOSURE TO CARBON MONOXIDE IN NOTTINGHAM, UK. Atmospheric Environment, Vol. 31, No. 7, 1997, pp. 1003–9.
51. Clifford, A. Predicting Traffic Patterns, One Honda at a Time. MSN Auto, , 2012.
52. Schrank, D. TTI's 2012 URBAN MOBILITY REPORT. 2012.
53. U.S. Energy Information Administration (EIA). Independent Statistics and Analysis. https://www.eia.gov/. Accessed May 1, 2019.
54. Fagnant, D. J., and K. M. Kockelman. The Travel and Environmental Implications of Shared Autonomous Vehicles, Using Agent-Based Model Scenarios. Transportation Research Part C: Emerging Technologies, Vol. 40, 2014, pp. 1–13.
55. Brown, A., B. Repac, and J. Gonder. Autonomous Vehicles Have a Wide Range of Possible Energy Impacts (Poster). Presented at the Workshop on Road Vehicle

Automation, 16 July 2013, Stanford, California; Related Information: NREL (National Renewable Energy Laboratory), 2013.

56. Brown, A., J. Gonder, and B. Repac. An Analysis of Possible Energy Impacts of Automated Vehicles, Springer, Cham, pp. 137–153.
57. Santos, A., N. Mcguckin, H. Y. Nakamoto, D. Gray, S. Liss, A. Santos, N. Mcguckin, H. Y. Nakamoto, D. Gray, S. Liss, and C. Systematics. Summary of Travel Trends: 2009. National Highway Transportation Survey. 2011.
58. Bureau of Transportation Statistics. Freedom to Travel. 2003.
59. Fulton, L., D. J. Mason, D. Meroux, and U. C. Davis. Three Revolutions in Urban Transportation. 2017.
60. Techcrunch. Let's Talk About Uber, Congestion And Urban Air Quality | TechCrunch. https://techcrunch.com/2015/08/26/uber-london-impact/. Accessed Mar. 5, 2019.
61. Shared-use Mobility Center. What Is Shared Mobility? | Shared-Use Mobility Center. https://sharedusemobilitycenter.org/what-is-shared-mobility-old/. Accessed Mar. 5, 2019.
62. Todd Schneider. Taxi, Uber, and Lyft Usage in New York City - Todd W. Schneider. https://toddwschneider.com/posts/taxi-uber-lyft-usage-new-york-city/. Accessed Mar. 5, 2019.
63. Martin, E. W., and S. A. Shaheen. Greenhouse Gas Emission Impacts of Carsharing in North America. IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS, Vol. 12, No. 4, 2011. https://doi.org/10.1109/TITS.2011.2158539.
64. Christian, R., and M. Emma. Moses - Mobility Services for Urban Sustainability: Environmental Assessment. Report WP 6. Stockholm, 2005.
65. Martin, E., and S. Shaheen. Impacts of Car2go on Vehicle Ownership, Modal Shift, Vehicle Miles Traveled, and Greenhouse Gas Emissions: An Analysis of Five North American Cities. Berkeley, CA, 2016.
66. Cohen, A., and S. Shaheen. Planning for Shared Mobility. 2016.
67. Rayle, L., D. Dai, N. Chan, R. Cervero, and S. Shaheen. Just a Better Taxi? A Survey-Based Comparison of Taxis, Transit, and Ridesourcing Services in San Francisco. Transport Policy, Vol. 45, 2016, pp. 168–178. https://doi.org/10.1016/J.TRANPOL.2015.10.004.
68. Streets Blog NYC. It's Settled: Uber Is Making NYC Gridlock Worse – Streetsblog New York City.
69. Martin, E., S. Shaheen, E. Martin, and S. Shaheen. The Impact of Carsharing on Public Transit and Non-Motorized Travel: An Exploration of North American Carsharing Survey Data. Energies, Vol. 4, No. 11, 2011, pp. 2094–2114. https://doi.org/10.3390/en4112094.
70. Vasconcelos, A. S., L. M. Martinez, G. H. A. Correia, D. C. Guimarães, and T. L. Farias. Environmental and Financial Impacts of Adopting Alternative Vehicle Technologies

and Relocation Strategies in Station-Based One-Way Carsharing: An Application in the City of Lisbon, Portugal. Transportation Research Part D: Transport and Environment, Vol. 57, No. October, 2017, pp. 350–362. https://doi.org/10.1016/j.trd.2017.08.019.

71. Ma, Y., B. Yu, and M. Xue. Spatial Heterogeneous Characteristics of Ridesharing in Beijing–Tianjin–Hebei Region of China. Energies, Vol. 11, No. 11, 2018, p. 3214. https://doi.org/10.3390/en11113214.
72. Chen, T. D., and K. M. Kockelman. Carsharing's Life-Cycle Impacts on Energy Use and Greenhouse Gas Emissions. Transportation Research Part D: Transport and Environment, Vol. 47, 2016, pp. 276–284. https://doi.org/10.1016/j.trd.2016.05.012.
73. Martin, E. W., and S. A. Shaheen. Greenhouse Gas Emission Impacts of Carsharing in North America. IEEE Transactions on Intelligent Transportation Systems, Vol. 12, No. 4, 2011, pp. 1074–1086. https://doi.org/10.1109/TITS.2011.2158539.
74. Minett, P., and J. Pearce. Estimating the Energy Consumption Impact of Casual Carpooling. Energies, Vol. 4, No. 1, 2011, pp. 126–139. https://doi.org/10.3390/en4010126.
75. Nurhadi, L., S. Borén, H. Ny, and T. Larsson. Competitiveness and Sustainability Effects of Cars and Their Business Models in Swedish Small Town Regions. Journal of Cleaner Production, Vol. 140, 2017, pp. 333–348. https://doi.org/10.1016/j.jclepro.2016.04.045.
76. Dowlatabadi, M., and H. Namazu. Characterizing the GHG Emission Impacts of Carsharing: A Case of Vancouver. Environmental Research Letters, Vol. 10, No. 12, 2015, p. 124017. https://doi.org/10.1088/1748-9326/10/12/124017.
77. Liimatainen, H., M. Pöllänen, and R. Viri. CO2 Reduction Costs and Benefits in Transport: Socio-Technical Scenarios. European Journal of Futures Research, Vol. 6, No. 1, 2018, pp. 1–12. https://doi.org/10.1186/s40309-018-0151-y.
78. Firnkorn, J., and M. Müller. What Will Be the Environmental Effects of New Free-Floating Car-Sharing Systems? The Case of Car2go in Ulm. Ecological Economics, Vol. 70, No. 8, 2011, pp. 1519–1528. https://doi.org/10.1016/j.ecolecon.2011.03.014.
79. US EPA, O. Overview of the Clean Air Act and Air Pollution.
80. US EPA. MOVES2014a User Guide. 2015, p. 266.
81. Center for Urban Transportation Research. A Report on the Contribution of Automated Vehicles to Reduced Fuel Consumption and Air Pollution. 2013.
82. Strategies to Advance Automated and Connected Vehicles: A Primer for State and Local Decision Makers.
83. Zmud, J., T. Williams, M. Outwater, M. Bradley, N. Kalra, and S. Row. Updating Regional Transportation Planning and Modeling Tools to Address Impacts of Connected and Automated Vehicles, Volume 2: Guidance. Transportation Research Board, Washington, D.C., 2018.