The Impact of Vehicle Electrification and Autonomous Vehicles on Air Quality in the United States

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ABSTRACT

The impact of electric vehicles (EVs) on energy demand, emissions and air quality has been explored in a number of studies, many of which assess EV impacts in the context of various energy supply scenarios along with increased demand. Many however, do not take into account, the impact of self-driving vehicles (Autonomous Vehicles (AV)) in quantifying EV effects. AV utilization is expected to increase significantly in the future, along with electrification of the US fleet, which will result in increased vehicle miles traveled (VMT) from Shared Automated Vehicles (SAVs), yet its impact on air quality is seldom explored within the EV context. In this study, we assess the impact of EVs in future years under a Relaxed Energy Policy (REP) where future aggressive emissions reductions have been relaxed across multiple emission sectors. Here, the impact of vehicle electrification on light duty passenger vehicles under a less ambitious future energy policy and 2050 projected meteorology under the Representative Concentration Pathway 4.5 in the mobile sector is explored along with emission changes across other sectors for the month of July. Both 2050 future projection scenarios (with and without electrification), when compared with 2011 emissions showed significant improvement for all primary and secondary pollutants, a result reflective of current regulations. The impact of increased VMTs due to AV utilization between the two 2050 scenarios (with/without electrification) also showed reductions due to fleet electrification in NO_x (max ~0.5ppb), O_3 (max~1ppb), and daily maximum 8HR O_3 (max~1ppb) for the summer month of July.

Keywords: Air quality, Emissions, Fleet electrification, Autonomous Vehicles.

INTRODUCTION

The transportation sector has a significant influence on the environment, as it consumes about 29%[1] of all energy use within the United States and is largely responsible for the bulk of emissions within cities[2, 3]. Mobile emissions from the transportation sector, such as particulate matter ($PM_{2.5}$), Nitrous Oxides (NO_x) and Volatile Organic Compounds (VOCs) are known to have adverse environmental impacts and health effects[4-6]. The last two listed pollutants, are key in the formation of tropospheric ozone (O_3), which too has adverse impacts on human health and the environment[7]. Cleaner standards imposed by the federal government on Internal Combustion Vehicles (ICVs) have been effective at reducing primary emission quantities of these pollutants[8, 9], and a study by Song et al. (2008)[10] found that mobile emission reductions as a result of federal regulations made a difference in daily maximum hourly ozone of -10ppb in a number of case runs. While there is an ongoing and current trajectory in regulations for cleaner vehicles, a number of future scenarios might impact or attenuate their regulatory impact. Firstly, there is the risk that energy policies that pushed for clean fuel and combustion standards could be rolled back, stalled or dismantled in the future by policy makers for various reasons[11]. But more to the point, even in scenarios where such policies remain, obtaining a neutral carbon footprint for climate mitigation solutions or obtaining zero emissions will be near impossible with an ICV. This problem is further exacerbated with expected Vehicle Miles Traveled (VMT) and population increases, which will happen as cities continue to expand[12]. Therefore, it is very likely that motor emissions will continue to have a substantial impact on city air quality.

Many states such as New York[13] plan to achieve a zero carbon footprint by 2050, and a significant change in auto fleet make up could play a major role in this regard. Achieving a zero carbon footprint and zero emissions in urban cities can be achieved with the help of Electric Vehicles (EVs) which consist of Hybrid Electric Vehicles (HEVs), Plug-in-Hybrid Electric Vehicles (PHEVs), and Battery Electric Vehicles (BEVs). So far, EVs have shown potential, in a number of studies in reducing primary pollutant emissions and secondary pollutants, although it's full effect in the context of tighter vehicle emission regulations are somewhat modest. For instance, Nopmoncol et al. (2017)[14] conducted a study where 2030 electrification of the on-road and off-road mobile sector were evaluated and noted modest improvements in ozone of 1ppb and $PM_{2.5}$. However, they found that the changes were largely attributed to improved regulations on on-road ICV vehicles despite using a mix of cleaner fuels with the marginal increase on electricity grid demand (~5%) from EVs. The study concluded that most of the improvements with electrification were seen from the off-road sector vehicles like lawn mower riders and marine vehicles, not the on-road electrical vehicles, the former of which had not been subject to regulations like on-road sector vehicles. Observing appreciable improvements in secondary pollutant concentrations like ozone from electrification is further complicated, as noted in Schnell et al. (2019)[15] because it varies by season, region etc. Similar to other studies, Schnell et al. (2015)[15] found that ozone decreased more in urban centers but slightly increased in rural locations in the summer and the opposite in the winter with an electrified fleet.

While there is general consensus that the criteria pollutants are generally reduced with fleet electrification, especially if a clean mix of energy generation[14, 16] is utilized, its effects on ozone and $PM_{2.5}$, in conjunction with ongoing emission controls make it questionable to see how much of an impact we will see. Under current energy mix scenarios, the impact of EVs might appear to be modest in conjunction with federal policies unless energy generation shifts largely to renewable or cleaner sources[17]. However, under different Representative Concentration Pathways (RCP) and warmer climate scenarios, the impact of EVs might be more noticeable than ICVs, particularly in regard to ozone formation[18]. Further, EV effects depending on the power train (i.e. HEV, PHEV and BEV) is a significant factor in emission reductions as well, as found by Onat et al. (2015)[17].

The future effects of EVs will not only be influenced by the energy mix and power train, but also by the increased demand in EV charging above what would have been marginal levels[16] when additional effects of vehicle electrification, like Automated Vehicles (AVs) lead to an increase in VMT. Electrification allows for automation, and with automation, will come the ability for many to utilize more traveling options through the self driving feature of AVs and Shared Automated Vehicles (SAVs). Self driving vehicles are expected to have larger market share (~ 36%)[19] of electric vehicles by 2050[20] and the impact of this projection is not only expected to change vehicle ownership in households, but could increase the use of SAVs, and in doing so, give vehicle access to different social economic groups that may otherwise not have access to such vehicles for multiple factors[21]. As SAV utilization via automation and electrification is expected to increase annual VMTs[19], the combination of electric cars in addition to increased vehicle miles traveled could have a significant impact on emissions.

Not many studies have looked at the impact of AVs and SAVs with electrification. Further, while some look at the impact of electrification with increased VMTs in future years, not many address it with the full impact of other sectors (point, area etc.) changes under relaxed energy policies, as well as the effect of climate change and projected meteorology. Here, we do a full assessment in this regard and incorporate a mix of electric vehicles types unlike other studies that largely focus on one or two types of electric vehicle for a scenario in a limited scope. We focus on electrification of the light duty vehicle (LDV) fleet in the year 2050 with a mix of power train technology (i.e. HEV, PHEV and BEV). We make use of Chemical Transport Models (CTMs) and an EPA mobile emission simulator in this study to simulate air quality under two temporal base line scenarios (2011 and 2050 without electrification) to compare the 2050 electrification scenario to. Our objective in this study is to answer the following:

1) How will increased vehicle miles from automation impact air quality in the future?
2) What will be the impact of electrification and power train of the vehicle fleet on air quality?
3) What will be the impact of meteorology on air quality in 2050?
4) What will be the impact of relaxed energy policies with fleet electrification?
5) What is impact of improved ICV efficiency on electrification impacts?

METHODS

The methods outlined in this section largely focus on scale up projections of vehicle miles traveled and emission changes from the mobile sector for the electrification scenario in 2050 for the LDV fleet. To produce these projections, we utilize EPA’s 2011 NEI emission inventory, a national household survey and EPA emission factors from MOVES.

VMT and VPOP projections for 2050 electrification

With the exception of the 2011 base case, emissions projection calculations were required for all 2050 scenarios. The 2011 National Emission inventory (NEI)[22] was used for the base case of 2011, while 2050 projected emissions were scaled up using statistical projections of future energy demand and emissions factors. While more details can be found in Shen et al. (in submission)[23], we briefly detail some specifics here in subsequent paragraphs. To incorporate the impact of an electrified vehicle fleet on the 2050 projected emissions, a household survey dataset, developed by the Department of Civil, Architectural and Environmental Engineering at University of Texas Austin was used to obtain vehicle miles traveled and projected vehicle populations of the fleet by power train. We briefly describe the data set here but more details can be found in Quarles et al. (2020)[19] and Lee et al.(2020)[24].

The survey data was an analysis of US household adoption rates between 2017 and 2050, of electric and automated vehicles as well as use of shared automated vehicles. A statistical representative sample size of 1414 US households was used in the survey and the description of survey data for each household covered the annual number of miles traveled in each household if using an automated vehicle (AV) or a human operated vehicle (HV). Also taken into account was the pricing of keeping and not keeping HV capabilities present in the vehicle along with AV features to test the adoption rates. A total of 12 scenarios were performed for 5%, 7.5% and 10% AV pricing reduction rates with HV option (i.e. AV with/without HV, AV/HV and 3 price ranges). For purposes of our research, the 5% price adjustment with HV capability retention scenario was used.

In addition to vehicle automation and its impact on adoption rate purchase, the power train makeup for the vehicles in the survey consisted of the following a) Gasoline, b) Diesel, c) Plug in Electric Hybrid (PHEV), d) Hybrid Electric Vehicles (HEV) and e) Battery operated vehicles (BEV). The survey results were projected from 2017 to 2050 and included fleet turnover data and the number of miles driven with SAVs. The survey showed a general decrease in household VMT (personal miles) driven and an increase in miles driven with SAVs. A breakdown of the survey data after scaling up to national estimates is shown in figure 1.

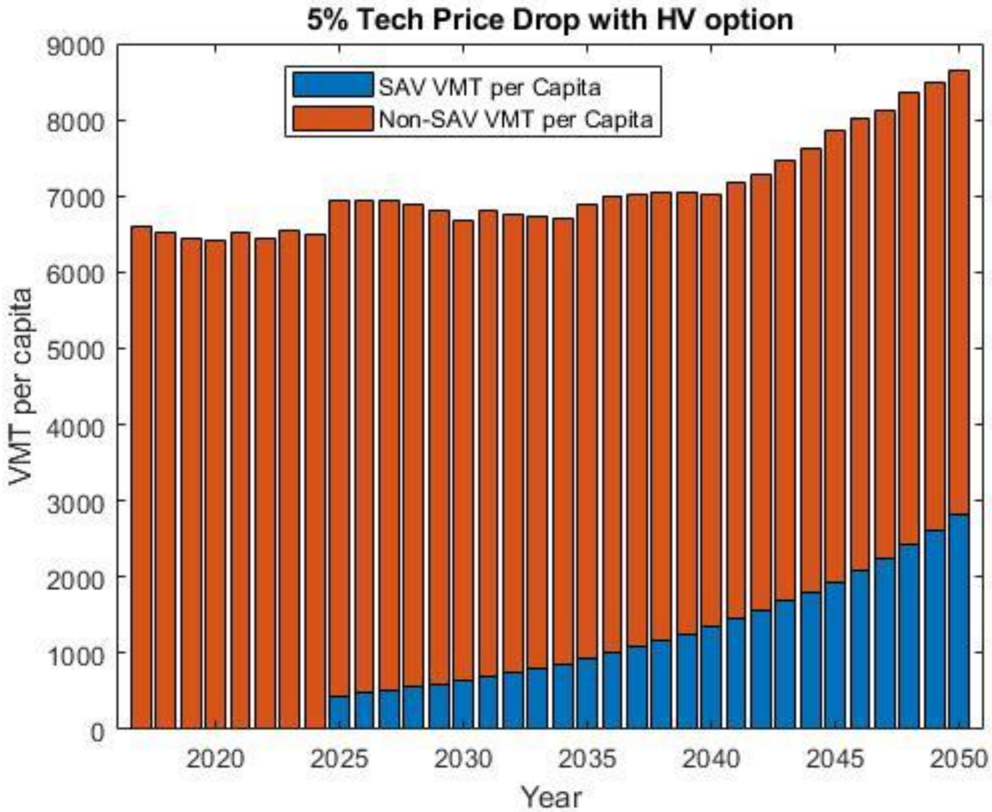


Figure 1: Break down of VMT per Capita Miles.

Statistical projections of household and national population were used to scale up the survey data to obtain a national estimation of vehicle miles traveled by power train make up for 2050 electrification scenario. Projected household and population data tables from Statista[25, 26], together with 2011 NEI data were used here. The scale up to total actual VMT and VMT by power train distribution from the survey were obtained using the Statista tables in conjunction with the 2011 NEI data to get the temporal and Vehicle Population (VPOP) data. The month of July was chosen to evaluate the impact of ozone in the summer months and 2050 was chosen to allow time for sufficient market share of EVs.

Emission Estimates and scale up factors

The scaled up VPOP and VMT data were used as inputs into a mobile emission estimator to generate emissions for different pollutants. Here we used the EPA's Motor Vehicle Emissions Simulator (MOVES2014b)[27] to develop scale up factors for mobile emissions in 2050 electrification scenario. The MOVES program has been used in similar studies such as those by Pan et al. (2019)[28] and Gunseler et al. (2017)[29]. As described on the EPA website[30], MOVES is a 'state-of-the-science emission simulator' that captures emissions from mobile sources using different emission factors (EFs) for different vehicle types (i.e. motorcycles, LDVs) in a variety of automotive processes such as running exhaust or evaporative processes. Emission factors in MOVES are estimated or cataloged by the EPA in MOVES as far back to 1960 to 2050 (although MOVES year input starts at 1990) for all vehicle types and power trains. The EFs also vary (for each vehicle) under different driving conditions (i.e. speed and road type) and meteorology (i.e. temperature and humidity). Due to emission controls and technological improvements, emission factors for all fuel types are expected to improve in future years and MOVES captures these changes. More information about MOVES can be found on the EPA site[30].

Although MOVES is used widely for mobile estimations, one of the short comings, in studies such as this as noted by Guensler et al. (2017)[29], is that MOVES does not have a source category for HEV or PHEV vehicles. Studies that tend to utilize MOVES, follow suit of Guensler et al. (2017)[29] in looking at HEVs by treating them as gasoline vehicles and in many cases, will treat PHEVs as BEVs. However, while HEVs at higher speeds and PHEVs (when not in electric mode) tend to run similar to gasoline vehicles, there is no mechanism in MOVES to account for low speeds when HEVs engage in regenerative breaking to run on electric mode or when PHEVs deplete their electric battery power source and switch to gasoline. Another short coming of using MOVES in this study is the lack of fuel economy when calculating fuel differences. For instance, it is more efficient to directly convert electrical energy to mechanical energy as opposed to a conventional gasoline vehicle where gasoline is converted to heat and pressure before mechanical energy, thereby having many losses. Yet, as noted by Guensler et al., (2017)[29], the fuel economy for fully electric vehicles and gasoline vehicles are listed as the same in MOVES.

As MOVES does not have emissions factors for hybrid or plug in hybrid electric cars, but for BEVs, we develop a binning category to split the miles to account for some of the short comings described in previous paragraph. For HEV vehicles, we split the VMTs proportions by speed and road type. Using 2011NEI emissions, we calculate the proportion of VMTs driven on the average speed and road type. We assume that HEVs will run primarily on the electric motor at a certain speed threshold and thus simulate the proportion of miles as BEVs for that speed range and above that as gasoline cars. With PHEV cars, we use a baseline that PHEV battery can drive up to a certain mile range before the gasoline engine is utilized and split the VMTs based on the number of VMTs driven in households with one or two cars. For one car households, we subtract the yearly average of miles driven for households and place the number of miles above battery range as gasoline and assign the VMTs driven for the second car in the household largely as BEV miles traveled.

We used a slightly different method to approach the final scale up from 2011 to 2050 than outlined in Pan et al., (2019)[28]. Where they modified EFs generated by MOVES to get spatially gridded emission input files, we used the calculated VMT and VPOP obtained in the preceding steps as direct inputs into MOVES to get 2050 emissions estimates. The MOVES output of emissions were then scaled with 2011 NEI totalized emissions to obtain emission scale up factors which were then used to multiply the Sparse Matrix Operator Kerner Emissions (SMOKE)[31] generated 2011 gridded emission files to get 2050 gridded input field for the Chemical Transport Model (CTM).

Meteorology Projections

As outlined in Shen et al. (in submission)[23], climate and meteorology predictions were made using the bias-corrected output data from the National Center for Atmospheric Research's Community Earth System Model version 1 (CESM1)[32] which were spatially downscaled to 36-km resolution using the Weather Research and Forecasting Model version 3.8.1[33]. The climate scenario we chose was the Representative Concentration Pathway (RCP) 4.5, being representative of a climate scenario with moderate increase in temperature. During the WRF downscaling, spectral nudging was applied to temperature, horizontal winds, and geopotential heights, with a wave number of 3 in both zonal and meridional directions and a nudging coefficient of 3×10^{-4} s^{-1} for all the variables.

Energy and emission projections from other sectors

The energy projection from the other sectors, such as residential, commercial, industrial, and power sectors were estimated using the National Energy Modeling System operated at Georgia Institute of Technology (GT-NEMS) [23, 34, 35]. GT-NEMS is a computational general equilibrium model based on the 2018 distribution of the U.S. Energy Information Administration (EIA)'s National Energy Modeling System. The estimates were conducted using less stringent Relaxed Energy Policies (REP). Biogenic emissions were estimated using an updated version of Biogenic Emission Inventory System (BEIS)[36]. To get the future biogenic emissions, BEIS was driven by the 2050 meteorology. The simulation showed a 13% increase in biogenic emission compared to the current levels. Additional details can be found in Shen et al.(in submission)[23].

Air quality modeling with Chemical Transport Models (CTM)

Similar to the study by Pan et al. (2017)[28], we used the SMOKE-WRF-CMAQ set up to model atmospheric concentrations. SMOKE was used together with 2011 NEI emissions to generate gridded emissions together with meteorology projections from Weather Research Forecasting Model (WRF)[37]. Then scale up factors (as outlined in previous section) were applied to the gridded SMOKE emissions to scale up to emissions in 2050 for all the emission sectors sources like area and point. Scale up factors computed by Shen et al. (in submission)[23] were used to scale up emissions from other sectors in the 2050 REP base case. For the 2050 electrification scenario, the mobile sector was scaled up using computed emission factor results from MOVES as outlined in the previous section. Of note, the 2050 REP base case mobile sector does not consider electrified vehicles.

The Community Multiscale Air Quality (CMAQ) modeling system v5.0.2 with Chemical Bond (CB) mechanism 5 was used to simulate the impact of atmospheric process (transport, deposition, reactions etc.) and emission changes on air quality. Details for the model are documented in Byun et al., (2006)[38]. The simulation runs were conducted for the summer month of July at a 36km x 36km grid resolution over the entire United States. To fully assess the impact of climate with emission changes, we use 2050 projected meteorology and 2050 projected BEIS for all cases.

Scenario simulations

The set up for the run is outlined below and in Table 1. We consider three scenarios with the following specifications.

- Emissions Temporal: 2011 and 2050 (July)
- Meteorology: 2050 Projected Meteorology
- 2050 Energy Policy: 2050 Relaxed Energy Policy (REP)
- Resolution: 36 km X 36km grid size.

3 Simulation Cases for emissions

1. 2011 Emission Base Changes with 2050 projected meteorology and 2050 BEIS.
2. 2050 Projected Emissions under REP with 2050 projected meteorology, 2050 BEIS, and 2050 emissions from transportation VMT but no fleet power train changes.
3. 2050 Projected Emissions under REP with 2050 projected meteorology, 2050 BEIS, and 2050 emissions from transportation VMT and fleet power train changes.

Data Analysis

The changes in NOx, SOx, $PM_{2.5}$ O_3-8HRMax, and ozone are assessed in this study under the three scenarios. All scenarios are conducted under the same meteorology so that the impact of emissions changes in the same climate scenario can be clearly assessed and to help quantify the effect of potential emission reductions due to electrification. We not only explore the spatial profile of each pollutant, but we also assess the spatial and nominal concentration differences between all three scenarios. As noted by Song et al.

(2008)[10], the impact of emissions reductions are likely to be more significant between the 2011 base case and the 2050 projected scenarios due to the magnitude of emission differences based on the time involved and enacted regulation effects, than between both 2050 scenarios. So a 'difference' comparison between the two future scenarios will provide a slightly better quantification of electrification impact.

Case	*1*	*2*	*3*
Scenario Year	2011	2050	2050
Ref_Base Case	NA	1	1/2
Future Energy policy (REP/Aggressive)	N/A	REP	REP
Marginal Energy Adjusted for EV Charging on the grid	NA	N/A	No
Meteorology	2050	2050	2050
Climate: Representative Concentration Pathway	4.5	4.5	4.5
Biogenic emission file	BEIS 2050	BEIS 2050	BEIS 2050
Electrification Scenario	None	None	5%_with HV

Table 1: Scenario runs

RESULTS

<u>Pollutant Concentration Spatial profile</u>

We used CMAQ to generate output concentration for primary pollutants NOx, SOx, VOC and $PM_{2.5}$ and the secondary pollutant O_3 for the month of July in 2011 and 2050 under the scenarios listed in the Methods section. The hourly and daily values were averaged over the entire month and plotted in figure 2 over the entire continental United States at a 36km x 36km grid resolution.

2050 projected emissions (2050 REP Base)[23] under the relaxed energy scenario are compared with 2011 base emissions under the same meteorological conditions to assess the impact of emission changes under similar climate scenarios. Results in figure 2 show that despite increasing future demand, future emissions decrease substantially in 2050. This decrease reflects the impact of increasing efficiency controls and emission regulations over the last two decades in all sectors sources like point sources (i.e. Electrical Generating Units (EGUs)), to the mobile sector and area (i.e. residential homes) sector. The impact of these changes on both mobile and EGUs is particularly noticeable when looking at the spatial distribution of NOx emissions in the NOx plots (Figures 2a-c).

The impact of tighter regulations and controls on $PM_{2.5}$ and SO_2 on the EGUs yielded improvements in this regard when 2050 scenarios were compared to 2011 Base Case (Figures 2d-f, Figures 2m-o). Most of these changes were observed in the southeastern region of the country and are also documented in Hennerman et al. (2016)[39].

The regulations also had an impact on ozone, an effect which has been observed in other studies by Henneman et al.(2017, 2017)[40, 41] as well and others[42]. The concentration and spatial distribution of monthly averaged ozone over the whole region and daily averaged 8 hour maximum ozone (O_3-8HRMax) show noticeable improvements in 2050 when compared to the 2011 base case, especially in the eastern and western regions. As both 2011 Base Case and 2050 REP Base Case runs were conducted using the same meteorology and biogenic emissions, it is clear that these results are largely a reflection of changing emissions.

Of note, the observations between 2011 Base Case and 2050 REP Base Case were spatially similar to the 2050 electrification scenario. The impact of electrified fleet of this scenario is not as notable with most of the species with the exception of NOx. From the plot of figure 2c, the NOx spatial distribution captures the impact of an electrified fleet in the future year scenario along major interstate roadways. While there is a slight improvement in the fleet electrified scenario for ozone, this is mainly observed in the eastern region for monthly averaged O_3 and not much difference was observed for the daily maximum 8-hour average concentration with respected to the 2050 REP base case.

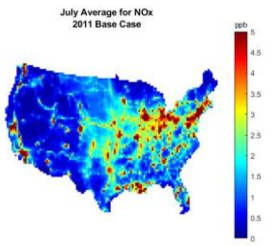
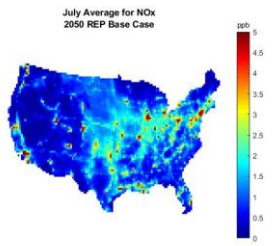
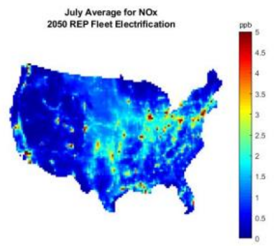
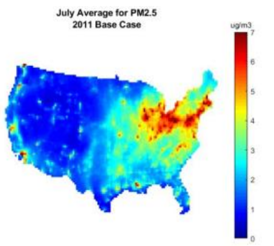
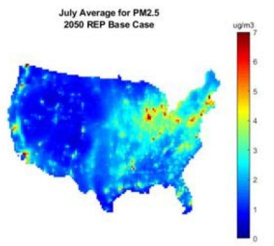
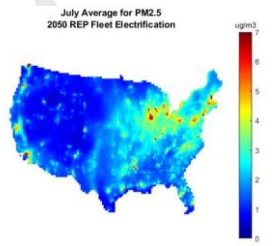
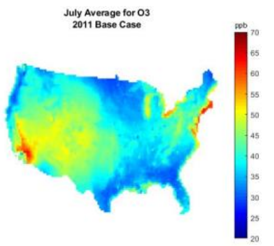
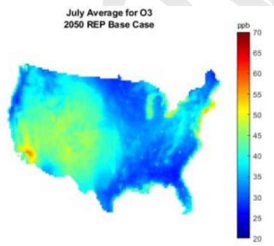
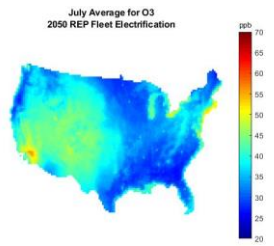
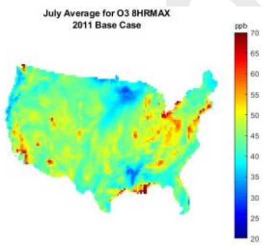
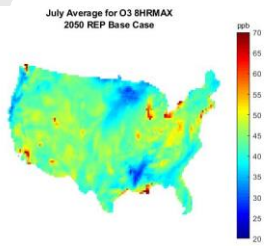
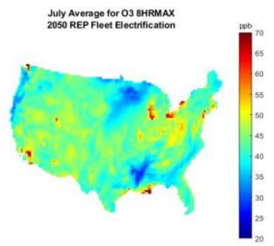
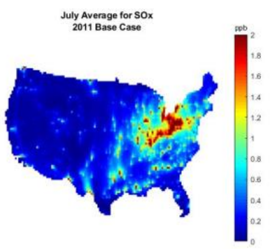
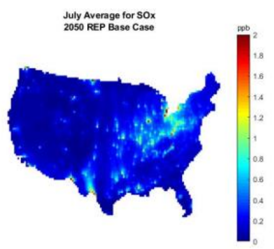
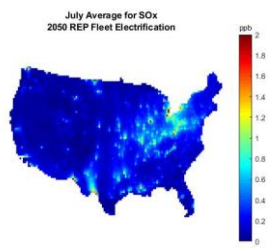
Pollutant	2011 Base Case	2050 REP Base Case	2050 Electrification
NOx	a 	b 	c 
$PM_{2.5}$	d 	e 	f 
O_3	g 	h 	i 
O_3 8hr max	j 	k 	l 
SO_2	m 	n 	o 

Figure 2: Plots show the monthly averaged spatial results for NOx, O_3, $PM_{2.5}$, Maximum 8hr O_3 and SO_2 for the month of July in 2011 and 2050.

Emissions base comparisons

For this analysis, the 2050 electrification results are compared to the 2011 and 2050 REP base cases by taking the difference between their respective concentration fields for each pollutant. The results here are plotted in figure 3. As mentioned earlier, in the case of NOx, there is a substantial reduction in emissions for both 2050 future scenarios from the 2011 base case, despite expected demand. NOx reductions range from 0 to 1ppb across the country, with the highest reductions seen mainly in the southeast, which once again reflects the regulation impact on EGUs. Between both future year scenarios, there are modest overall reductions of NOx emissions in the future electrified fleet scenario though mainly on roads. As seen in figure 3c, the future year scenario, under an electrified fleet under the 5% adoption rate shows reduction values along roadways as high as 0.5pbb from the 2050 REP base case.

Primary emissions differences of particulate matter show a different spatial pattern than NOx between future years and the 2011 base year. In the southeast, we see an obvious reduction in $PM_{2.5}$ in orders of 2 ug/m^3 for $PM_{2.5}$ and a negligible change overall in other areas of the country between the 2011 and 2050 scenarios. Between the 2050 scenarios, electrification seemed to show a decrease in primary pollutants, which was expected, however the change was miniscule, reflecting the efficiency in motor vehicle emission regulations. However the reduction in $PM_{2.5}$ from electrification covered a broader spatial extent and was not restricted solely near roadways.

For the monthly averaged ozone concentration and daily averaged O_3-8HRMax, the impact of electrification between the two future scenarios is more evident (Figures 3g-l). Overall, there is a about a 0-1ppb decrease in daily 8hr maximum ozone through the map and we see a decrease of about 1-2ppb in monthly averaged ozone. The direct impact of electrification ozone here is clear and similar results are observed in other studies[15].

Changes in sulfur dioxide spatial concentrations between the 2011 base year and future years are observed. The spatial plots in figure 3(Figures 3m-o) show notable reductions in SO_2 emissions mainly in the south east from regulations on power plants emissions and negligible changes elsewhere. However, between the two 2050 future scenarios, there is a slight increase in SO_2 concentration. SO_2 was the only pollutant to show an increase in concentration with the electrification scenario over the 2050 REP Base case. However, this did not come from the electrification of the light duty passenger fleet, but more from increased vehicle miles and emissions from heavy duty vehicles like buses and trucks that use diesel fuel. However, this change is negligible and largely small (~ 0.005 ppb).

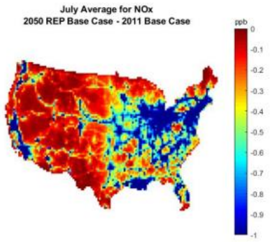
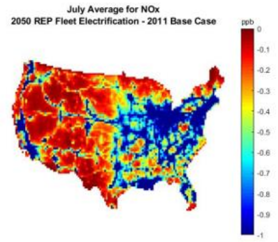
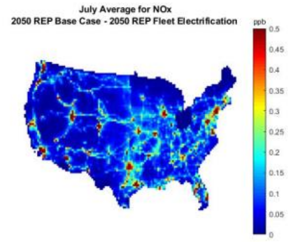
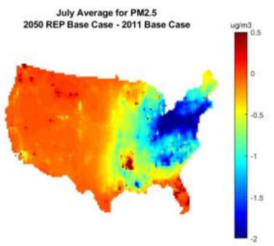
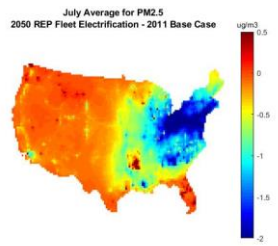
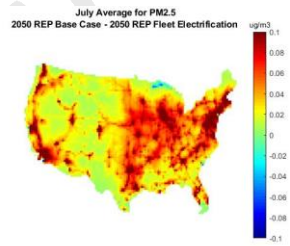
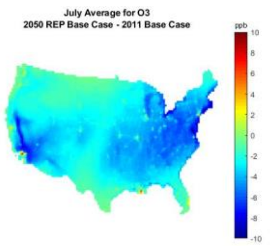
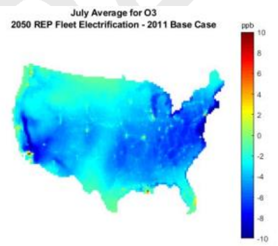
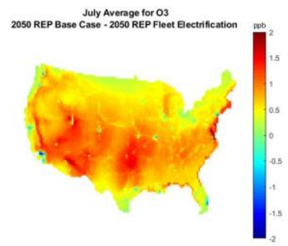
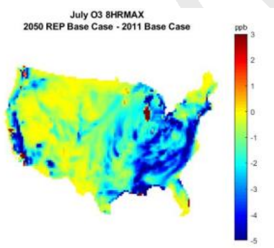
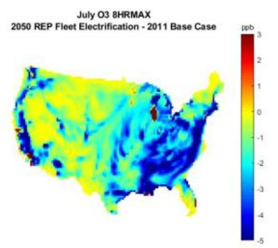
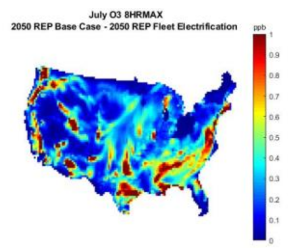
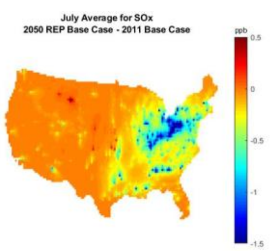
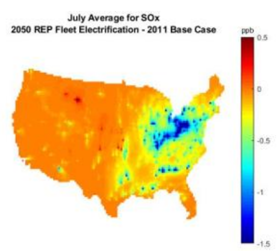
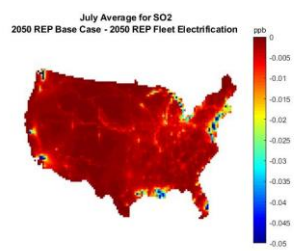
Pollutant	2050 REP – 2011 Base	2050 Electric –2011 Base	2050 REP – 2050 Electric
NOx	a 	b 	c 
$PM_{2.5}$	d 	e 	f 
O_3	g 	h 	i 
O_3 8hr max	j 	k 	l 
SO_2	m 	n 	o 

Figure 3: Plots show the difference between base cases of monthly averaged spatial results for NOx, O_3, $PM_{2.5}$, Maximum 8hr O_3 and SO_2 for the month of July in 2011 and 2050.

DISCUSSION

Similar to previous studies, modest decreases in pollutant species were observed with electrification except for SO_2, although this increase was largely due to contribution from increased VMTs from diesel vehicles and was minuscule in magnitude. However, the impact of electrification on SO_2 emissions might have been more significant with marginal increases in electricity demand. However, studies by Pan et al., (2019)[28] and Nichols et al.,(2015)[16], show that increases in energy demand are expected to be miniscule and in light of the observed effect of emission controls on EGUs, it is not expected to substantially change results here.

Though we did not consider the incremental demand on electricity consumption from PHEVs and BEVs here, the increased electricity demand of the electrified fleet could increase SO_2 emissions and possibly NOx and $PM_{2.5}$ with a less clean fuel mix[43]. A study by Li et al., (2016)[44] which incorporated incremental energy demand showed an increase in primary pollutants of SO_2 and NOx from power plants with a less clean fuel mix. Future work would incorporate the added demand load from SAV increased VMT on electricity charging to evaluate the impact with different energy mixes.

The plots in figure 3 clearly show the effect of emission reductions and electrification of the vehicle fleet between 2011 and 2050 on the pollutants. The results show reduced $PM_{2.5}$ primary emissions, especially in the east coast, and substantive NOx reductions from both regulation and electrification of the fleet. The 2011 and 2050 reductions for NOx, SO_2 and $PM_{2.5}$ are largely noted in the south east due as a result of tighter regulations on the energy center which is largely located in that region. Similarly, most of the substantive ozone improvements between 2011 and 2050 largely appear to be regionally located, although this appears to happen in both the south east and west coast. In general however, between years 2011 and 2050, there is a noticeable decrease in daily maximum 8Hr O_3 throughout the country.

The impact of fleet electrification in 2050 can be seen with NOx along the interstate roadways. $PM_{2.5}$ reductions from fleet electrification are generally more spatially spread out in the south east, highlighting the impact of dispersion and particulate formation in the atmosphere. While the impact of electrification on $PM_{2.5}$ is more spatially distributed, the magnitude of the reduction is minor (~ 0.1 ug/m3) as tail pipe emissions from ICVs are also expected to be quite low in the future.

The electrification effect on ozone is quite evident in the results shown in Figure 3. While ozone is lower in the future scenarios, electrification still yields modest reductions of about 1 to 2ppb. Even more modest reductions in daily averaged maximum ozone are noted with an improvement of about 1ppb in most areas in the electrification scenario. Of note, ozone reductions were observed throughout the contiguous land area with electrification in 2050.

When comparing the results of the future years, the results show that EVs will not have a significant impact with respect to current emission regulations in all sectors and with highly efficient ICVs. Similar results were also observed by Brady et al., (2011)[45]. In their study, they also observed that while EVs made an impact in emission reductions, their overall changes were minimal. Given the current energy mix, if marginal increments were to be taken into account, results could find that EV adoption might further increase the amount of emissions, as has been noted in a few studies, although this is also highly dependent upon the EV power train as well[17]. This becomes important if eventually all the cars become fully electric as all transport will be powered by electrical grid. Under a relaxed energy policy scenario, this might result in more pollution, although it is likely to be concentrated near the power energy sources.

Many studies show some impact of EVs (in regards to LCA GHG) for total life cycle compared to high efficient ICV under less CO_2 intensive power mixes is further minimized[46]. However, the impact under even cleaner scenarios is more obvious. PHEVs and EVs in particular are shown to offer such benefits under cleaner energy fuel mixes, although when compared to more efficient ICV vehicles could be modest. The study by Wu et al., (2012)[47] illustrates this point by showing a much cleaner mix of energy would be better to promote EVs mainly in areas with high coal combustion to have any benefit against efficient ICV vehicles.

Under clean energy scenarios, meteorological and climate projections with different RCP pathways could show an advantage of EVs over ICV vehicles however, especially in regard to secondary pollutants like ozone and particulate matter. The spatial distribution of ozone and $PM_{2.5}$ in figures 3f and 3i under the electrified scenario highlight this potential benefit. In warmer climate and with cleaner fuel sources, there is a potential for EV cars to reduce the number of peak ozone days under NOx limited scenarios[48].

The impact of different EV adoption under more carbon intensive RCPs on air quality is potentially significant. Studies by Shen et al. (in submission)[23] and Zhang et al. (2017)[18] show that more ozone exceedances are expected under warmer climates. The spatial distribution of positive ozone abatement (figure 3i) in the electrified scenario highlights the benefits of minimizing NOx on roadways. Therefore, it is possible that EVs might be effective in mitigating ozone exceedances and ozone concertation in a more adverse climate.

CONCLUSIONS

Across the board, the 2050 electrification scenario saw positive reductions in all primary pollutants except SO_2 when compared with the 2050 REP base year. However, due to continuing emissions reductions in EGUs with current emission standards, the benefits are modest, even under relaxed energy policies. Thus quantifying future impact of EVs on overall net emissions may not be so noticeable. However, the effect could be a beneficial change in spatial distribution of the pollutants as seen with particulate matter and ozone where reductions are not necessarily regional. With different climate scenarios, the impact of EVs might be more discernable in this regard.

Another potential benefit of EVs is the shift of mobile emissions from urban sources to the rural sectors where the energy is more likely produced[49]. This could either significantly reduced the human health exposure by reduction in population, or create an inequity in exposure to pollution.

Although the changes and benefits for EVs depend on the energy mix and may not be obvious under current emission regulations, its potential in producing zero emissions cities as power plants use more renewable sources will likely increase its adoption into the market.

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AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: Armistead G. Russell, Ph.D, Kara M. Kockelman, Ph.D., P.E., Abiola S. Lawal, Huizhong Shen, Ph.D; data collection: Abiola S. Lawal, Jooyong Lee, Yilin Chen, Huizhong Shen, Ph.D; analysis and interpretation of results: Abiola S. Lawal, Huizhong Shen, Armistead G. Russell, Ph.D, Kara M. Kockelman, Ph.D., P.E., Yilin Chen, Jooyong Lee; draft manuscript preparation: Abiola S. Lawal, Huizhong Shen, Yilin Chen, Jooyong Lee, Armistead G. Russell, Ph.D, Kara M. Kockelman, Ph.D., P.E.

All authors reviewed the results and approved the final version of the manuscript.

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