Comparisons of air quality impacts of fleet electrification and increased use of biofuels

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Received 17 February 2011
Accepted for publication 13 May 2011
Published 26 May 2011
Online at stacks.iop.org/ERL/6/024011

Abstract

The air quality impacts of the partial electrification of the transportation fleet and the use of biofuels (E85) were modeled for the Austin Metropolitan Statistical Area, based on a 2030 vision of regional development. Changes in ozone precursor emissions and predicted ozone, carbon monoxide and aldehyde concentrations were estimated for multiple electrification and biofuel scenarios. Maximum changes in hourly ozone concentration from the use of plug-in hybrid electric vehicles (PHEVs) for 17% of the vehicle miles traveled ranged from $-8.5$ to $2.2$ ppb, relative to a base case with no electrification and minimal biofuel use, depending on time of day and location. Differences in daily maximum 1 h ozone concentration ranged from $-2.3$ to $0.004$ ppb. Replacement of all gasoline fuels with E85 had a smaller effect than PHEVs on maximum daily ozone concentrations. Maximum ozone changes for this scenario ranged from $-2.1$ to $2.8$ ppb and the difference in daily maximum 1 h ozone concentrations ranged from $-1.53$ to $0$ ppb relative to the base case. The smaller improvements in maximum ozone concentrations associated with extensive (100%) use of biofuels, compared to a smaller (17%) penetration of PHEVs, suggests that higher levels of PHEV penetration may lead to even greater improvements; however, the higher penetration would require expansion of the electrical grid capacity. The air quality impacts of the PHEVs would then depend on the emissions associated with the added generation.

Keywords: plug-in hybrid electric vehicles (PHEVs), air quality, biofuels, E85, CAMx, ozone

1. Introduction

High concentrations of ground level ozone remain one of the most pervasive urban air quality problems worldwide, and vehicles are among the most significant sources of emissions leading to ozone formation (Cooper and Arbrandt 2004, Sawyer et al. 2000). The primary approaches to reducing vehicle emissions have historically been the development and deployment of emission and fuel evaporation control equipment, as well as regulation of vehicle fuel efficiency and gasoline taxation. Increasingly, however, alternative liquid fuels and vehicle electrification are being used as approaches for improving regional and urban air quality, as well as mitigating greenhouse gas emissions.

Plug-in hybrid electric vehicles (PHEVs) have attracted attention as promising approaches for reducing emissions from on-road mobile sources. Vehicles that commute less than 50 km day$^{-1}$ represent about 60% of all commuting vehicles in the United States (US Department of Transportation 2001), suggesting that many short trips could be accomplished purely on electrical power. PHEVs reduce on-road emissions by using electricity from the power grid as their source of energy; however, the use of PHEVs has the potential to increase emissions from stationary electricity generation units, depending on the nature of the electricity generating units used to charge the PHEV batteries.

The balance between potential emission increases due to increased electricity generation and decreased emissions from on-road vehicles has been examined in a number of studies. The Electric Power Research Institute (EPRI) and the Natural Resources Defense Council (NRDC) performed an environmental assessment of PHEVs for the year 2030 (EPRI;
Knipping and Duvall (2007). The study investigated the air quality impacts of PHEVs if 40% of US on-road vehicles were converted to battery power. The study used the Community Multiscale Air Quality (CMAQ) model to examine ozone mixing ratio, particulate matter concentrations, deposition of sulfate, total nitrogen and mercury concentrations. One of the important assumptions made in this study was that the new electricity generation capacity was met by increasing the load of current coal-fired generation units. The study did not account for additional emissions regulations or constraints in the future. The study showed that PHEVs would reduce exposure to ozone and PM, and reduce deposition rates for acids and mercury in most regions. However, some regions showed increases in ozone and PM exposure.

In another study, the net CO₂ emissions reductions due to electrifying the US fleet using the current electric grid were examined by Arar (2010). The results showed that the net change in CO₂ emissions (increase from power plants and decrease from on-road vehicles) would result in 23–58% reductions depending on the timing of the fleet conversion.

The Minnesota Pollution Control Agency (MPCA) (2007) conducted an analysis of air pollution emissions that would result if PHEVs entered the market in Minnesota. PHEVs lowered emissions of CO₂, CO, NOₓ, VOC and PM₂.₅ by 30–60%, relative to conventional vehicles but produced higher SO₂ emissions due to the coal-fired electricity generation necessary for battery recharging. Samaras and Meisterling (2008) provided a comparison of life cycle greenhouse gas emissions from PHEVs and conventional gasoline vehicles and found that PHEVs reduced greenhouse gas emissions by 32% compared to conventional vehicles if PHEV battery charging relied on the current patterns of US electricity generation. Larger reductions were found if the electricity generation was assumed to have a lower carbon intensity than current practice, and even under some higher carbon intensity electricity generation, life cycle greenhouse gas emissions decreased.

Thompson et al. (2009) extended these emission analyses by estimating changes in ozone concentrations associated with PHEV use, recognizing that changes in spatial and temporal distributions of emissions occur as the transportation fleet is electrified. The scenarios considered assumed replacement of 20% of the fleet of gasoline light-duty vehicles with PHEVs in the Pennsylvania, New Jersey and Maryland (PJM) region of the United States. The study assumed that the fuel to be used as feed to the electricity generating units (EGUs) to generate the additional electrical power for PHEV charging was coal, which likely represented a worst-case scenario with respect to emissions of ozone precursors and greenhouse gases. Still, the analysis demonstrated net reductions in regional ozone concentrations due to electrification.

More commonly than fleet electrification, the use of alternative liquid fuels has emerged as a strategy for reducing vehicular emissions. The Renewable Fuel Standard (RFS, Energy Independence and Security Act (EISA) of 2007) in the United States calls for the use of 36 billion gallons of renewable fuels in the transportation fleet by the year 2020. Most of the renewable fuels used to satisfy the RFS are expected to employ ethanol as a blending agent for gasoline; more limited amounts of biodiesel are expected. In addition, the Clean Air Act of 1990 requires the use of oxygenates (now almost exclusively ethanol) in many parts of the United States to improve regional air quality.

Niven (2005) examined the environmental impacts of using ethanol/gasoline blends on air pollutant emissions and greenhouse gas emissions. An 85% ethanol blend (E85) produced 27 times more acetaldehyde and formaldehyde compared with petroleum-based gasoline, but produced less VOC, benzene, and 1,3-butadiene emissions. E85 also exhibited lower evaporative emissions, since its vapor pressure is less than that of conventional gasoline. Life cycle CO₂ and other greenhouse gases emissions were reduced by 19%–70%, depending on the ethanol feedstock.

Sheehan et al. (1998) found that by replacing petroleum diesel with biodiesel, net life cycle CO₂ emissions were reduced, by 78.5% for neat biodiesel (B100) and by 15.7% for B20. Life cycle NOₓ and VOC emissions increased by roughly 10% and 35%, respectively, but net reductions in life cycle CO and PM emissions of 35% and 32%, respectively, were predicted. Numerous other analyses of changes in emissions from renewable fuels have been performed and are summarized in the regulatory impact assessment documentation for the RFS (EPA 2009).

Jacobson (2007) examined the potential effects of replacing gasoline with E85 on cancer, mortality and hospitalization for two geographic areas, Los Angeles and the United States as a whole. The effects of E85 use on human health were investigated with a three-dimensional photochemical grid model (GATOR-GCMOM; Jacobson 2007). Jacobson (2007) predicted that the 24 h daily maximum ozone concentration would increase by 3 ppb in the Los Angeles area due to the use of E85. Ozone related deaths were estimated to increase by 120 cases per year in Los Angeles and 185 deaths per year in the United States.

To summarize, multiple studies have examined the air quality impacts of either the electrification of the transportation fleet or the substitution of petroleum-based fuels with renewable fuels; however, few studies have performed direct comparisons of these two strategies. In one of the few analyses available, Jacobson (2009) compared the impacts of PHEVs and E85 versus gasoline assuming several electricity generation scenarios. The study investigated the changes in CO₂ equivalent emissions and mortality rate due to converting on-road light- and heavy-duty gasoline powered vehicles to either battery electric vehicles (BEVs), hydrogen fuel cell vehicles (HFCVs) or E85. The results of this study give the upper limit of benefits for the PHEV case since some scenarios assumed that the electricity generation options were derived from renewable energy resources. The results showed that replacing 100% of the US gasoline on-road vehicles with electric vehicles powered by wind could reduce CO₂-equivalent emissions by 32.5–32.7% and eliminate 15,000 air pollution premature deaths per year. However, biofuel options provide either no change or an increase in CO₂-equivalent emissions, and might increase the air pollution premature death rate up to 185 deaths yr⁻¹. The work reported here expands the comparisons between PHEV and biofuel...
Table 1. Electricity generation units in the Austin area, by fuel type (Austin Energy 2008).

| Facility name          | Number of units | Fuel type | Capacity (MW) |
|------------------------|-----------------|-----------|---------------|
| Decker Creek           | 2               | Gas       | 934           |
| Sand Hill Energy Center| 5               | Gas       | 501           |
| Sam Seymour            | 3               | Coal      | 1641          |
| (Fayette Power Project)|                |           |               |
| Sam Gideon             | 3               | Gas       | 620           |
| Lost Pines             | 2               | Gas       | 545           |
| Bastrop Energy Center  | 2               | Gas       | 540           |
| Sandow                 | 1               | Coal      | 600           |

scenarios by comparing widespread adoption of biofuels to fleet electrification assuming current electricity generation practices. The region around Austin, Texas is used as a case study.

2. Methods

The Comprehensive Air Quality Model with Extensions (CAMx; www.camx.com), a 3D Eulerian photochemical grid model, was used to examine the air quality benefits associated with PHEVs and biofuels. Model inputs include meteorological data, initial and boundary conditions, land use and land cover data, and emission inventories. The inventories include emissions from anthropogenic sources including stationary point sources, area sources, on-road mobile sources and non-road mobile sources, as well as emissions from biogenic sources.

The emission scenarios used were projected emissions developed for the year 2030, for the Austin, Texas metropolitan area (Song et al 2008, Webb et al 2008). Emissions were based on four urban growth scenarios, known as Envision Central Texas (ECT), which were developed for the Austin area based on an assumed doubling of population. Meteorological conditions were based on a historical 13–20 September 1999 high ozone episode in the Austin area, used for the development of Austin’s air quality plans submitted to the US Environmental Protection Agency. In this work, partial electrification of the transportation fleet was investigated over an urban development scenario that assumed extensive highway provision, and low-density and segregated-use development (Song et al 2008).

In modifying the emission estimates developed by Song et al (2008) to account for widespread PHEV use, the assumptions concerning the types of electricity generation used in recharging the PHEV batteries were based on the existing and anticipated electricity generation mix for the Austin region. The electricity generation grid around Austin is broadly representative of the Electric Reliability Council of Texas (ERCOT) grid. In the power generation facilities near Austin, natural gas provides 57.1% of the generation mix compared to 58% for ERCOT, Coal accounts for 21.9% and 23%, and nuclear facilities represent 7.6 and 7% for Austin and ERCOT respectively (Austin Energy 2008 and North American Electric Reliability Council 2006). However, using the power generation facilities near the Austin area to charge PHEVs would represent a worst-case scenario for the impact of EGU emissions on Austin air quality. Therefore, in this study, the marginal air quality impacts of charging PHEVs constitute an upper bound on the air quality impacts from EGUs.

The maximum electricity generation capacity in the Austin area is more than 5300 MW, with approximately 3140 MW generated from natural gas and 1 MW from solar. Approximately 274 MW are currently generated from wind and used by the City of Austin as purchased power. Furthermore, there was approximately an additional 265 MW of capacity scheduled for installation at the end of 2009, including 165 MW from wind. Thus, at the end of 2009, the total maximum capacity available was more than 5500 MW in the Austin area. Austin area power plants that use natural gas and coal as fuels are shown in table 1 with their capacities.

The electricity delivered by Austin area power plants during the summer ozone season varies during the daytime hours with an average daily maximum peak load of more than 1900 MW (at 3:00 PM), as shown in figure 1 (EPA 2008).

Figure 1. Hourly electricity consumption for the Austin area based on 2008 ozone season data (EPA 2008).

The concept explored in this work is for PHEVs to use the excess capacity from electricity generation units during nighttime hours for charging, after vehicle use during the daytime. Charging of PHEVs during nighttime hours is assumed to occur between 10 PM and 1 AM. Other studies have assumed nighttime charging to occur between 10 PM and 8 AM (Stephan and Sullivan 2008), and so one of the scenarios to be considered in this work examines the sensitivity of results to the timing of emissions. The electricity demand during the 10 PM–10 AM window is significantly lower than peak demand and could be met without the addition of generation units. Three different scenarios for charging PHEVs were considered in this work, all of which assumed that 17% of all passenger vehicle miles traveled would be accomplished with PHEVs operating on battery power: the PHEV use was set based on the maximum amount that could be supported by the average unused capacity between 10 PM and 10 AM.

The following three scenarios were evaluated.

(i) Scenario 1 (17% PHEVs without EGU controls): use the same electricity generating units, but with a different temporal profile by charging PHEVs during nighttime hours; emissions per unit of electricity generated remain constant. The new emissions profile is shown in

Table 1. Electricity generation units in the Austin area, by fuel type (Austin Energy 2008).
(iii) Scenario 3 (17% PHEVs with EGU controls): same as

Electricity generation temporal profile (EPA 2008) 

Figure 3. Electricity generation temporal profile (EPA 2008) currently used in Austin and emission rate temporal profile used in PHEV scenario 3.

Figure 2. Base case electricity generation profile and emission rate temporal profile in scenario 1.

case. On-road mobile source emissions were modified for this scenario based on the work of Jacobson, which assumed that the NOx emission rates for these vehicles decreased by 30%, while the CO and VOC emission rates increased by 5% and 19.6% respectively (Jacobson 2007). The VOC emission compositions assumed by Jacobson were also employed. The temperature dependence of emissions at low temperatures, as reported by Ginnebaugh et al. (2010), was not included because the typical daytime and nighttime temperatures in the Austin area in winter rarely reach the low temperatures required for this effect to be significant. The average daytime and nighttime temperatures in the winter season range between 18 and 6°C (National Weather Service 2003).

The method used to calculate the emission reductions associated with the use of PHEVs is based on the average electricity consumption estimates for PHEVs from the Electric Power Research Institute (EPRI; Knipping and Duvall 2007). The additional MWh available during the nighttime hours was converted to total vehicle miles traveled (VMT) by distributing the VMT to three types of light-duty vehicles based on the percentage of these vehicles in the fleet, as shown in table 2. The average PHEV electricity consumption factors from EPRI (Knipping and Duvall 2007) are greater than the estimate of 300 Wh/mile from the Pacific Northwest National Laboratory (PNL; Kintner-Meyer et al. 2007). Thus, the EPRI factors represented a more conservative case and were selected for this work. Table 2 shows the distribution of light-duty gasoline vehicles and the average economy factors from EPRI.

Federal highway statistics for 2002 (DoT 2002) provided the percentage of vehicles in each category. Using the average fuel economy factors and the percentage of each category of light-duty vehicles, the total VMT in the five-county Austin MSA was determined to be 14.2 million miles traveled per day, as shown in table 2. The total VMT for light-duty gasoline vehicles from Song et al. (2008) is 82.4 million. Thus, the reduction in the VMT (estimated for 2030) for light-duty gasoline vehicles, due to their replacement with PHEVs, is 17% from the base case. Table 3 shows the emissions of VOC and NOx (ton per day) for the base case (Song et al. 2008) and the PHEV scenarios.

### Table 2. Light-duty gasoline vehicle types and associated fuel economy factors (Knipping and Duvall 2007).

| Vehicle type                  | Light-duty passenger fleet (%) | Average fuel economy factor (Wh/mile) | VMT (10^6 miles) |
|-------------------------------|-------------------------------|--------------------------------------|------------------|
| Passenger cars                | 65                            | 318.2                                | 10.3             |
| Gas truck (SUV)               | 13.50                         | 394.2                                | 1.7              |
| Gas truck                     | 21.50                         | 493.2                                | 2.2              |

### Table 3. Emissions of VOC and NOx (ton per day) for the base case (Song et al. 2008) and the PHEV scenarios.

| Categories                  | Base case | Scenario 1 | Scenario 2 | Scenario 3 |
|-----------------------------|-----------|------------|------------|------------|
| On-road mobile              | 22.0      | 18.4       | 18.3       | 18.3       | 15.3       | 15.3       |
| Non-road mobile             | 23.2      | 9.5        | 23.2       | 9.5        | 23.2       | 9.5        |
| Area                         | 214.3     | 20.6       | 214.3      | 20.6       | 214.3      | 20.6       | 214.3      | 20.6       |
| Point                        | 3         | 2.8        | 3.3        | 3.03       | 3          | 2.8        | 3          | 2.8        |

### Figure 2

This represents a worst-case scenario (of the three considered in this work) for the air quality impacts of transportation fleet electrification.

(ii) Scenario 2 (17% PHEVs without additional EGU emissions): in this scenario, vehicle charging is assumed to occur throughout the day; however, it is also assumed that either EGUs will install additional controls or the additional demand for electricity due to charging PHEVs can be met through clean energy resources such that emissions in both cases remain the same as the base case shown in figure 2.

(iii) Scenario 3 (17% PHEVs with EGU controls): same as scenario 2, but applying additional controls on emissions from EGUs during peak generation hours resulting in a flat temporal profile of emissions. Figure 3 shows temporal profiles for emissions from current electricity generation (scenario 2) (EPA 2008) and for the emission rates used in this scenario.

Scenarios 2 and 3 both represent best cases for fleet electrification (no increases in emissions due to electricity generation), but illustrate the impacts of different temporal distributions of emissions.

In addition to the PHEV scenarios, a scenario in which E85 is used as a replacement for petroleum-based fuel for light-duty gasoline vehicles was considered. In this scenario, it is assumed that 100% of the vehicle fleet uses E85 (E85 100% scenario). Point source emissions from power plants were not altered for the E85 scenario relative to the base scenario used in Austin and emission rate temporal profile used in PHEV scenario 3.

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and NOx (tons per day) for the base case (Song et al. 2008) and the PHEV scenarios.

Four metrics were used to evaluate and compare the ozone concentration impacts of the PHEV scenarios and the E85 scenario: maximum 1 h average ozone concentration, total area above a threshold ozone concentration, time integrated area above threshold ozone concentration and a measure of total daily population exposure.

Two threshold ozone concentrations (60 and 70 ppb) were used for the area of exceedance metrics. For the fourth metric, related to total daily population exposure, a 0 ppb threshold was used in order to provide a more comprehensive assessment of the impacts of these scenarios relative to the base case scenario of Song et al. (2008). The metrics are described below.

(1) Maximum 1 h ozone concentration:

\[ M_{\text{max},1 \text{ h}} = \text{Max}(C_{g,h}) \]

where \( C_{g,h} \) is the 1 h \( O_3 \) concentration in (ppb), in the grid cell \( (g) \) and at time \( (h) \). This metric was calculated by examining all ground level 1 h averaged ozone concentrations in the Austin area during each day, and choosing the maximum 1 h averaged ozone concentration.

(2) Total area above a threshold ozone concentration of 60 or 70 ppb:

\[ M_{\text{Area total}} = \sum_g A_g \text{max}(\delta_{g,h}) \]

\[ \delta_{g,h} = \begin{cases} 0, & C \leq 60 \text{ (or 70)} \\ 1, & C > 60 \text{ (or 70)} \end{cases} \]

where \( A \) is the area of the grid cell \( g \) in (km\(^2\)). This metric was calculated by determining whether the ground level 1 h averaged ozone concentration exceeded a threshold concentration of 60 ppb (or 70 ppb). If ozone concentration exceeds the threshold in a grid cell at any time during the day in the Austin area, the area of the grid cell is added to the total area of exceedance.

(3) Time integrated area above a threshold ozone concentration of 60 or 70 ppb:

\[ M_{\text{Time area}} = \sum_n \sum_g A_g \delta_{g,h} \]

\[ \delta_{g,h} = \begin{cases} 0, & C \leq 60 \text{ (or 70)} \\ 1, & C > 60 \text{ (or 70)} \end{cases} \]

(4) Total daily population exposure:

\[ M_{\text{Time pop}} = \sum_n \sum_g P_g \delta_{g,h} \]

\[ \delta_{g,h} = \begin{cases} 0, & C \leq 60 \text{ (or 70)} \\ C - 60, & C > 60 \text{ (or 70)} \end{cases} \]

where \( P_g \) is the population in grid cell \( g \). This metric was calculated by multiplying the population in the cell by the difference between the maximum ozone concentration and the threshold ozone concentration of 60 or 70 ppb, if the ozone concentration at the grid cell exceeded the threshold. The value was calculated for each grid cell in the five-county Austin metropolitan area and summed over the day. A threshold ozone concentration of 0 ppb was also considered in this work in order to gain additional insight into ozone exposure in the area of interest.

3. Results and discussion

The photochemical modeling simulations were compared for different days of the week, which exhibited a range of traffic patterns. In addition to ozone concentrations, predicted daily maximum carbon monoxide (CO) and aldehyde concentrations were examined for each scenario and compared with similar predictions for the base case.

3.1. Mobile source emissions

NOx, VOC and CO emission rates from on-road mobile sources vary between strategies and strategies have different effects for different species. Table 4 shows NOx, VOC and CO daily emissions for the base case and the differences in the emissions in the five-county Austin area due to the PHEV scenarios and the E85 100% scenario.

| Species | Tons/day of each species for base case | 17% PHEVs without EGU controls | 17% PHEVs without changes in EGU emissions | 17% PHEVs with EGU controls; no diurnal variation in emissions | E85 100% |
|---------|--------------------------------------|-----------------------------|-----------------------------------------------|------------------------------------------------|--------|
| NOx     | 18                                   | -3.1                        | -3.1                                          | -3.1                                         | -5.2   |
| VOC     | 22                                   | -3.7                        | -3.7                                          | -3.7                                         | 4      |
| CO      | 480                                  | -81                         | -81                                           | -81                                          | 24     |

The maximum 1 h ozone concentration in all ground level grid cells in the Austin area was determined for each hour of each day, and compared with the threshold of 60 or 70 ppb. If there was an exceedance in any grid cell, then the area of this grid cell in this hour was added to the area of exceedance. Areas of exceedance for each hour were summed over all hours in the day.

3.2. Daily maximum 1 h and 8 h average \( O_3 \) concentrations

Figure 4(a) shows the maximum difference in daily 1 h ozone concentrations for the PHEV scenarios and the E85 100% scenario.
Figure 4. Maximum ozone difference from the base case for: (a) daily maximum 1 h ozone concentration (the base case averaged 78.8 ppb, with a range of 70.2–84.7 ppb), (b) daily maximum 8 h ozone concentration (the base case averaged 71.6 ppb, with a range 67.1–75.8 of ppb) and (c) maximum change in hourly O3 concentration between the base case and the PHEV scenarios and E85 100%. Note that a negative difference means a decrease in O3 concentration relative to the base case, and a positive one means an increase in O3 concentration relative to the base case and the ‘⋆’ sign shows the average difference in ozone concentration.

These values represent the maximum differences in the daily maximum 1 h ozone concentration in the Austin five-county area regardless of the day, the time of day, or the geographic location. Stars in the bar charts indicate the averages over multiple episode days of the differences in maximum ozone concentration, regardless of the time of day or geographical location.

Reductions in daily maximum 1 h averaged ozone concentrations were observed for all episode days except 17 September when a slight increase of 0.004 ppb was predicted for PHEV scenarios 1 and 3. These reductions are due to the shifting of NOx emissions from daytime to nighttime hours. For the E85 scenario, maximum predicted ozone concentrations decrease, despite an increase in VOC and CO emissions, relative to the base case. The results indicate that reductions in NOx emissions are more effective than reductions in VOC emissions with respect to reducing maximum 1 h ozone concentrations. These results are consistent with those from previous studies that have shown that ozone formation in the Austin area is NOx sensitive, with VOC sensitivity under limited conditions along the main interstate highway (IH-35) in central Travis County (The Capital Area Planning Council 2004, Song et al 2008).

A similar analysis of the strategies was also conducted based on daily maximum 8 h averaged ozone concentrations. Figure 4(b) shows similar patterns to figure 4(a). For both the 1 and 8 h averaged maximum daily ozone concentrations, the maximum reductions were achieved using 17% PHEVs with no additional EGU emissions and a constant temporal profile for emissions. This suggests that the temporal pattern of the
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Figure 5. (a) Maximum increase for 17% PHEVs without EGU controls, (b) maximum decrease for 17% PHEVs without EGU controls, (c) maximum increase for 17% PHEVs with EGU controls, (d) maximum decrease for 17% PHEVs with EGU controls, (e) maximum increase for E85 100% and (f) maximum increase for E85 100% relative to base case on 18 September.

EGU emissions is more important, in the scenarios examined in this work, than the locations or magnitudes of the EGU emissions. This indicates that charging PHEVs should be avoided during peak generation hours.

In addition to differences in area-wide daily maximum 1 and 8 h ozone concentrations between the base case and the PHEV and E85 scenarios, the maximum and minimum differences in 1 h ozone concentrations that occurred across the Austin MSA regardless of time of day or magnitude were investigated. The minimum difference ($O_{\text{test base}}$) represents the maximum benefit in daily 1 h O$_3$ concentration that could be achieved, while the maximum difference shows the maximum degradation in air quality (increase in ozone concentration). Maximum differences in 1 h ozone concentrations ranged from $-8.5$ to $+2.2$ ppb for all PHEV strategies (all times of day, not just times of maximum ozone) relative to the base case (figure 4(c)). The range of concentration changes for the E85 100% scenario was $-2.1$ to $+2.8$ ppb.

Figure 5 shows the spatial distribution of the maximum differences ($O_{\text{test base}} - O_{\text{base}}$) in hourly O$_3$ concentrations on 18 September regardless of time of day. The maximum reduction for the 17% PHEVs with EGU controls scenario was observed in the early morning (4:00 AM) and located in central Bastrop County, with the maximum increase in the evening (8:00 PM).
Figure 6. Maximum difference in per cent of (a) total area of exceeding, (b) time integrated area and (c) population exposure above a threshold of 60 ppb for the PHEV scenarios and E85 100% relative to the base case. Note that a negative change means a decrease in total area or total daily population exposure exceeding a threshold, and a positive change indicates an increase in total area or total daily population exposure exceeding a threshold and the ‘⋆’ sign shows the average difference in per cent.

3.3. Total area, time integrated area and total daily population exposure exceeding a threshold 1 h $O_3$ concentration of 60 ppb

Figure 6(a) shows the maximum difference in percentage of total area exceeding a threshold of 60 ppb for the PHEV and E85 scenarios relative to the base case. The area of exceedance for the base case averaged 9960 km$^2$ over the episode days modeled in the simulations, with a range of 6704–12 240 km$^2$.

Figure 6(b) shows the difference in percentage of total time integrated area of exceedance (threshold of 60 ppb) relative to the base case. Figure 6(c) shows the percentage change in total daily population exposure exceeding a threshold of 60 ppb.

The behavior of the area of exceedance metric is complex. The total area exceeding the threshold concentration (figure 6(a)) shows a similar pattern to the maximum ozone concentrations, i.e., the PHEV scenarios showed, on average, greater ozone reductions than the E85 scenario. In contrast, however, if the area of exceedance is time integrated, or if a measure of exposure to concentrations above 60 ppb is estimated, the E85 scenario produces greater ozone reductions than the PHEV scenarios. If the concentration threshold is changed to zero, however, the PHEV scenarios lead to reductions in the measure of total daily population exposure, ranging from $-0.51\%$ to $-0.12\%$, while the E85 results in more modest reductions ($<0.2\%)$ or slight increases.

As the threshold ozone concentration increases, the percentage reductions in the measure of total daily population exposure for the PHEV and E85 scenarios relative to the base case also increase. However, a higher percentage of reduction does not necessarily reflect a higher reduction in the magnitude of the metric of population exposure, since there are fewer grid cells that exceed the higher threshold.
3.4. Impacts on CO and aldehyde concentrations

Consistent with the changes in emissions, the use of PHEVs results in decreases in predicted CO concentrations, while the use of E85 increases CO concentrations. Figure 7 shows the maximum difference in CO concentrations for all episode days for PHEV scenarios and E85 100% relative to the base case. (The base case averaged 1425 ppb, with a range of 601.1–1922 ppb.)

The reductions are observed during the morning rush hour (8:00 AM) due to the decrease in CO emissions from the vehicle fleet. Also, the maximum reductions are concentrated along the main transportation highway (IH-35).

As shown in table 4, emissions of VOCs decrease for the PHEV scenarios by 17%. In contrast, VOC emissions increase by as much as 20% for the 100% E85 scenario. This is due in part to the increased acetaldehyde emission rate, which is a dominant VOC species produced from the ethanol combustion reaction (Winebrake et al. 2001).

Figure 8 shows predicted daily maximum difference in aldehyde concentration for the PHEV scenarios and E85 100% relative to the base case. In general, the use of PHEVs with or without additional EGU controls is predicted to decrease both VOC emissions and aldehyde concentrations, while the E85 scenario increased aldehyde concentrations.

4. Conclusions

The results showed that the differences in daily maximum 1 h ozone concentrations due to the PHEV strategies ranged from −2.3 to 0.004 ppb and for the E85 strategy ranged from −1.53 to 0 ppb relative to the base case. The maximum differences in 1 h ozone concentrations regardless of time of day ranged from −8.5 to 2.8 ppb for all strategies relative to the base case. The largest reductions were observed for the PHEV scenarios, while the maximum increase occurred for the E85 scenario. Similar patterns were observed for 8 h averaged concentrations.

The differences between the PHEV strategies indicated that the temporal pattern of emissions can be important in impacting ozone concentrations, suggesting that battery charging scenarios may be a critical factor in assessing the air quality impacts for fleet electrification. The maximum ozone concentration benefits for PHEV use would likely be achieved by reducing emissions from EGUs during peak generation.
hours. That is either EGUs install additional controls during peak generation hours (as in scenario 3) or the additional demand on electricity due to charging PHEVs should be met through clean energy resources (as in scenario 2). In addition, the complex spatial patterns of emissions and ozone formation can lead to complex behaviors when alternative metrics for air quality (e.g., population exposures to ozone concentrations above a threshold) are considered. In this work, thresholds of 60 and 70 ppb were chosen for these alternative metrics, since these are ozone concentrations that are being considered for a potential new standard. It should be noted that metrics at these exposure levels will not represent all health effects, since scientific evidence shows no threshold or level below which there is no health effect for ozone, as reported by the EPA Clean Air Scientific Advisory Committee (CASAC 2011). Readers interested in a more thorough discussion of the impact of threshold values on this work should see the cases examined by Alhajeri (2010), which include metrics at other thresholds, including zero.

This work indicates that PHEVs can improve the air quality in urban areas by reducing the ozone levels compared to biofuels. However, the impacts of the strategies considered in this work on local and regional air quality are not limited to ozone. For example, although PHEVs have shown promising results in terms of reducing daily maximum ozone concentrations, they have also been associated with higher SO₂ emissions than conventional gasoline vehicles due to the electricity generation necessary for battery recharging. PHEVs have the potential to reduce the particulate matter from vehicle exhaust associated with conventional gasoline vehicles, but higher SO₂ emissions could contribute to acid rain and secondary particulate matter formation. However, with the reduced SO₂ intensity of the future grid due to applying a cap and trade program (for example, Acid Rain Program) on SO₂ in the US, such emissions will decrease. As emission and generation patterns for electricity generation change, the air quality impacts of PHEV use will also change. In addition, impacts such as water use should be considered. Water use and grid capacity may become critical factors for PHEV strategies, especially in regions with water scarcity and limited generation capacity (King and Webber 2008a, 2008b, Lemoine et al. 2008). The National Research Council (National Research Council 2010) reports on many of these impacts, and for the air quality impacts examined in this work the findings reported here are consistent with the findings reported by the NRC.

Overall, while many measures of air quality are improved more by a partial fleet electrification than by conversion to E85, the patterns are complex. Also, the results presented here apply only to Austin, and the impacts of E85 or PHEVs when both changes to the transportation fleet are applied simultaneously, or applied in different regions, could be different. For example, combined application of PHEVs and biofuels can lead to greater ozone reductions, in some cases, than PHEV use alone. Interested readers can examine additional scenarios reported by Alhajeri (2010).

Finally, this work supports the conclusion that policies that promote charging of PHEV batteries from low emission electricity generation will achieve greater ozone reductions than the use of biofuels. However, the patterns of impacts are complex and should continue to be studied as alternative vehicle and power generation fleets emerge.

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