Supporting Information for

Effect of regional grid mix, driving patterns and climate on the comparative carbon footprint of gasoline and plug-in electric vehicles in the United States

Supporting Information

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1. Calculations:
In the following subsections we provide additional detail on the calculations used in our analysis.

1.1. Vehicle energy consumption

We use piecewise linear interpolation to estimate energy consumption of each vehicle at a variety of temperatures using laboratory test data measured at three test chamber temperature values:

\[
\begin{align*}
\epsilon_{ejm\delta}^{\text{INTERP}}(T) &= \epsilon_{ejm\delta T_2}^{\text{LAB}} + \frac{\epsilon_{ejm\delta T_2}^{\text{LAB}} - \epsilon_{ejm\delta T_1}^{\text{LAB}}}{T_2 - T_1} (T - T_2) & \text{if } T_1 \leq T \leq T_2 \\
&= \epsilon_{ejm\delta T_2}^{\text{LAB}} + \frac{\epsilon_{ejm\delta T_3}^{\text{LAB}} - \epsilon_{ejm\delta T_2}^{\text{LAB}}}{T_3 - T_2} (T - T_2) & \text{if } T_2 < T \leq T_3 \\
&= \epsilon_{ejm\delta T_3}^{\text{LAB}} & \text{if } T > T_3
\end{align*}
\]

where \(\epsilon_{ejm\delta}^{\text{INTERP}}(T)\) is the estimated consumption rate of fuel \(\epsilon\) per mile traveled for vehicle \(j\) in mode \(m\) on drive cycle \(\delta\) at temperature \(T\); \(\epsilon_{ejm\delta T}^{\text{LAB}}\) refers to dynamometer test results for fuel consumption measured at each of three temperatures \(T \in \{T_1, T_2, T_3\} = \{20^\circ F, 72^\circ F, 95^\circ F\}\), respectively; \(E = \{\text{electricity, gasoline}\}\) is the set of energy types; \(J = \{\text{Leaf BEV, Volt PHEV, Prius PHEV, Prius HEV, Mazda 3 CV}\}\) is the set of vehicles; \(M_j\) is the set of operation modes for vehicle \(j\); and \(\Phi = \{\text{UDDS, HWFET}\}\) is the set of drive cycles. The operation modes include charge-depleting (CD) mode, charge-sustaining (CS) mode, and conventional operation (CO), where \(M_j = \{\text{CD}\} \forall j \in J_{\text{BEV}}, \ M_j = \{\text{CD, CS}\} \forall j \in J_{\text{PHEV}}, \ M_j = \{\text{CS}\} \forall j \in J_{\text{HEV}}, \ M_j = \{\text{CO}\} \forall j \in J_{\text{CV}}, \) and the sets \(J_{\text{BEV}}, J_{\text{PHEV}}, J_{\text{HEV}}, J_{\text{CV}}\) partition \(J\) into subsets of BEVs, PHEVs, HEVs, and CVs, respectively.

The laboratory data \(\epsilon_{ejm\delta T}^{\text{LAB}}\) and resulting piecewise linear curves \(\epsilon_{ejm\delta}^{\text{INTERP}}(T)\) are provided in Section 3.1.

We use these piecewise linear curves to estimate consumption per mile traveled

\[
\epsilon_{ejm\delta l}^{\text{INTERP}}(T_{ldh})
\]

for each fuel \(\epsilon \in E\) in each vehicle \(j \in J\) in each operation mode \(m \in M_j\), at each location \(l \in L\), for each VMT profile \(v \in V_l\), on each day of the year \(d \in D\), each hour \(h \in H\), where \(|L| = 3109, |D| = 365, |H| = 24\), \(V_l\) is the set of NHTS VMT profiles associated with location \(l\), and \(\delta_l\) is the driving cycle assigned to location \(l\) based on its urbanization level:
\[ \delta_l = \begin{cases} \delta_{\text{HWFET}} & \text{if } u^\text{MSA}_l = \text{nonmetropolitan} \\ \delta_{\text{FTP}} & \text{if } u^\text{MSA}_l = \text{central} \\ \delta_{\text{COMB}} & \text{if } u^\text{MSA}_l = \text{outlying} \end{cases} \]

where \( u^\text{MSA}_l \) is the urbanization level of county \( l \) as defined by the U.S. Census Bureau, which classifies counties as nonmetropolitan, central and outlying. The energy consumption at combined drive cycle is a weighed average of highway and city energy consumptions which is estimated as follows:

\[ c_{\text{LAB}}^{\text{COMB}} = 0.55 c_{\text{LAB}}^{\text{FTP}} + 0.45 c_{\text{LAB}}^{\text{HWFET}} \]

To estimate the daily average electricity consumption per mile, we need to know how much each vehicle is driven at each hour of the day. We estimate this using the driving patterns from the NHTS dataset. For all the vehicles in \( V_l \), we distribute the driving durations into hourly bins throughout the day by looking at the start and end time of each trip, and we compute \( \Delta_{\text{DRV}}^{\text{h}} \), the amount of time (hours) each VMT profile \( v \in V_l \) spent driving during each corresponding one hour bin \( h \):

\[ \Delta_{\text{DRV}}^{\text{h}} = \sum_{\tau \in T_v} \begin{cases} 1 & \text{if } t^S_\tau \leq h - 1 \text{ and } t^E_\tau \geq h \\ 0 & \text{if } t^S_\tau \geq h \text{ or } t^E_\tau \leq h - 1 \\ \min(h, t^E_\tau) - \max(h - 1, t^S_\tau) & \text{otherwise} \end{cases} \quad \forall h, v \]

Where \( T_v \) is the set of trips for vehicle profile \( v \) in the data set and \( t^S_\tau \) and \( t^E_\tau \) are the start and end times of trip \( \tau \), respectively.

We then use the \( \Delta_{\text{DRV}}^{\text{h}} \) to obtain the daily weighted average energy consumption per unit distance

\[ c_{\text{LAB}}^{\text{INTERP}} = \frac{\sum_h \Delta_{\text{DRV}}^{\text{h}} c_{\text{LAB}}^{\text{INTERP}} (T_\text{lab})}{\sum_h \Delta_{\text{DRV}}^{\text{h}}} \quad \forall v \in V_l, d \in D \]

We then estimate the all-electric range (AER) for BEVs and PHEVs as follows:

\[ s_{\text{AER}}^{\text{lab}} = \begin{cases} c_{\text{BAT}}^j / c_{\text{LAB}}^{\text{INTERP}} & \forall j \in J_{\text{PEV}} \\ 0 & \forall j \in J_{\text{HEV}} \cup J_{\text{CV}} \end{cases} \]

\[ \forall l \in L, v \in V_l, d \in D, m = \text{electricity}, m = \text{CD} \]

where \( s_{\text{AER}}^{\text{lab}} \) is AER, and \( c_{\text{BAT}}^j \) is battery usable capacity (zero for HEV and CV).

To estimate the total daily average energy consumption in Wh, we need to determine the daily distance traveled by each vehicle profile. For all vehicle types except BEVs, daily distance traveled is equal to the distance provided for each vehicle profile in NHTS. For BEVs, we assume that if the distance driven in a
vehicle profile is longer than the AER of the BEV, the vehicle shortens travel on those days. In other words, the daily driving distance, $s_{jldv}^{\text{DAY}}$, is defined as:

$$s_{jldv}^{\text{DAY}} = \min \{s_{jldv}^{\text{AER}}, s_v\}, \quad \forall j \in J_{\text{BEV}}, \quad \forall l \in L_{ldv}$$

where $s_v$ is the daily VMT from NHTS vehicle profile $v$. Then, daily electricity consumption $C_{jldv}^{\text{ELEC}}$ and gasoline consumption $C_{jldv}^{\text{GAS}}$ for each vehicle and vehicle profile in each location on each day can be estimated as:

$$C_{jldv}^{\text{ELEC}} = \min \{s_{jldv}^{\text{AER}}, s_v\} \cdot c_{e, j lm_{ldv}}^{\text{DAY}}$$

$$C_{jldv}^{\text{GAS}} = \{\min \{s_{jldv}^{\text{AER}}, s_v\} \cdot c_{e, j lm_{ldv}}^{\text{DAY}} + \max (0, s_v - s_{jldv}^{\text{AER}}) \cdot c_{m_{ldv}}^{\text{DAY}}\}$$

$$\forall j \in J, l \in L, v \in V_l, d \in D, e_1 = \text{electricity}, e_2 = \text{gasoline}, m_1 = \text{CD mode}, m_2 = \text{CS mode}$$

**Electricity emissions.** CO$_2$ emissions due to electricity consumption vary depending on charge timing. We first determine the total charging duration for each vehicle as:

$$t_{jldv} = \frac{C_{jldv}^{\text{ELEC}}}{\eta_j f_j}, \quad \forall j \in J, l \in L, v \in V_l, d \in D$$

where $t_{jldv}$ is the total charging duration in hours, $\eta_j$ is the constant battery charging rate, and $f_j$ is the efficiency between the charger and the battery. In this study, we neglect the efficiency loss between the EVSE equipment and the charger, since it is much lower compared to the losses between charger and the battery.

Then we distribute the total charging duration into hourly bins assuming convenience charging for our base case simulations (i.e. charging starts right after the last trip of the day ends)

$$\Delta_{jldvh}^{\text{CHG}} = \sum_{n=0}^{1} \sum_{t \in L_{lv}} \left\{ \begin{array}{ll} 1 & \text{if } t_n^F \leq t_{n-1}^F + t_{jldv} \leq t_n^F \\
0 & \text{if } t_n^F \geq t_{n-1}^F + t_{jldv} \end{array} \right.$$

$$\min (t_n^F, t_n^E + t_{jldv}) - \max (0, t_n^E - t_{jldv}) \text{ otherwise}$$

$$t_n = h + 24n$$

$$\forall j \in J, l \in L, v \in V_l, d \in D, h \in H$$

Where $L_v$ is the last trip of the day for vehicle profile $v$, and we obtain $\Delta_{jldvh}^{\text{CHG}}$ which gives the charging duration that falls into hourly bin $h$. To test the effect of charging scheme on the results, we also run a
case where we assume delayed charging instead of convenience charging, which is assumed to start at midnight.

Regional average CO\textsubscript{2} emissions due to electricity consumption in grams/mile, \(y_{ji}^{\text{ELEC}}\), (averaged over all VMT profiles and days of the year) are then found by:

\[
y_{ji}^{\text{ELEC}} = \frac{\sum_{d} \sum_{h} \sum_{v} r_j \Delta j_{jvdh} (E_{ldh}^{\text{MEF}} + E_{ldh}^{\text{UPST}})}{\sum_{v} \sum_{d} s_{jvd}^{\text{DAY}}} \quad \forall j \in J, l \in L \tag{13}
\]

where \(E_{ldh}^{\text{MEF}}\) is the expected value of the regional time of day marginal emission factors in grams/kWh and \(E_{ldh}^{\text{UPST}}\) is the expected value of the regional time of day electricity upstream emissions in grams/kWh.

**Gasoline emissions.** Regional average CO\textsubscript{2} emissions due to gasoline consumption in grams/mile, \(y_{ji}^{\text{GAS}}\), (averaged over all vehicle profiles and days of the year) are then found by:

\[
y_{ji}^{\text{GAS}} = \frac{\sum_{v} \sum_{d} (G_{ldh}^{\text{COMB}} + G_{ldh}^{\text{UPST}})C_{jvd}^{\text{GAS}}}{\sum_{v} \sum_{d} s_{jvd}^{\text{DAY}}} , \quad \forall j \in J, l \in L \tag{14}
\]

where \(y_{ji}^{\text{GAS}}\) is the CO\textsubscript{2} emissions in grams due to gasoline consumption, \(G_{ldh}^{\text{COMB}}\) is the expected value of the gasoline combustion emissions factor in g/gal, and \(G_{ldh}^{\text{UPST}}\) is expected value of the gasoline upstream emissions factor in g/gal.

**Total emissions.** Total regional emissions are then defined as:

\[
y_{jl} = y_{jl}^{\text{ELEC}} + y_{jl}^{\text{GAS}} \quad \forall j \in J, l \in L \tag{15}
\]

2. **Sensitivity Analysis**

We analyze various additional cases to assess the sensitivity of the results to some key factors and assumptions. Specifically, we test the effect of:

- ignoring temperature variation,
- ignoring drive cycle differences,
- selecting vehicle profiles from NHTS based on county urbanization levels,
- assuming delayed charging instead of convenience charging,
- using a different set of MEFs from the literature, and
- using alternative temporal resolution for the MEFs.
Table 1 summarizes the case studies we perform and the decisions made for each case. For each case, only one decision or data set is changed and the rest of the assumptions are held the same as the base case. The difference in each case study is highlighted in the table.

2.1. **Base Case Analysis**

The base case analysis is explained in the main text, and some of the results are republished here in for ease of comparison.

2.2. **Case 1: Testing Importance of Temperature Effect**

We test the effect of temperature on the results by ignoring the temperature dependency of the energy (electricity and/or gasoline) consumption and assuming a single constant value per drive cycle, which we obtain by using the dynamometer test results at 72°F ($T_{\text{Ldh}} = T_2 \forall l \in L, d \in D, h \in H$).

Figure 1 and Figure 2 show results in comparison with the base case results. When the temperature effect is ignored, the comparison of PEVs to gasoline vehicles is more favorable to PEVs, especially in the northern US. The differences in results are due to the fact that temperature affects the hourly and daily energy consumption of the vehicles. This also leads to changes in charge times and durations, shifting the MEFs. The results indicate that temperature has a significant effect on comparative benefits of plug-in vehicles.
| Case                                      | ID        | MEFs                | Drive Cycle                          | Charging Scheme       | Vehicle Profiles | Temperature Effect | Vehicles Tested                  |
|------------------------------------------|-----------|---------------------|--------------------------------------|-----------------------|------------------|-------------------|-----------------------------------|
| Base Case                                | Base Case | SE 2011 Time of Day| Based on MSA Level (City, Highway or Combined) | Convenience           | State            | Included          | Leaf, Volt, Prius PHEV, Prius, Gasoline |
| Test importance of temperature           | Case 1    | Base                | Base                                 | Base                  | Base             | Ignored           | Leaf, Prius, Volt, Gasoline       |
| Test importance of regional driving patterns | Case 2    | Base                | Base                                 | Base                  | State Urban Rural| Base              | Leaf, Prius                      |
| Test importance of charging scheme       | Case 3    | Base                | Base                                 | Delayed               | Base             | Base              | Leaf                             |
| Test importance of drive cycle           | Case 4    | Base                | Combined only                        | Base                  | Base             | Base              | Leaf, Prius                      |
Figure 1  Nissan Leaf emissions compared to Prius and Mazda emissions. The first column shows base case results, and the second column shows results when the temperature effect is ignored.
Figure 2 Chevy Volt emissions compared to Leaf and Prius emissions. The first column shows base case results, and the second column shows results when the temperature effect is ignored.
2.3. Case 2: Testing the Importance of Regional Vehicle Driving Patterns

We base our assumptions of vehicle driving patterns (time of driving, driving distance) on vehicle driving profiles available in NHTS 2009 data. NHTS does not provide the exact location of the households surveyed; however, NHTS provides the state where the surveyed household resides as well as the urbanization level (urban or rural). In our base case simulations, we match the VMT patterns to counties based on their states only, i.e.: all counties in the same state have the same VMT patterns. To test the importance of this selection, we run another case where we match VMT profiles by states and urbanization level. With this assumption, all urban (or rural) counties in the same state are assumed to be represented by the same driving patterns. Figure 3 shows the results in comparison with the base case for PEVs vs Prius HEV, and Figure 4 shows the same comparison for PEVs vs CV. The difference in VMT profile allocation does not have a large effect on results.
Figure 3 Comparison of PEV emissions with HEV emissions: testing the importance of regional driving patterns, left: VMT pattern assigned by state level only; right: both state and urbanization level.
2.4. Case 3: Testing the Importance of Charging Scheme

In our base case simulations, we assume convenience charging, i.e. charging starts right after the last trip of the day. However, customers may be incentivized to charge at night in some regions, due to lower electricity costs\(^1\). To test the effect of the decision on charging scheme, we simulate a case where charging starts at midnight for all vehicle profiles simulated.

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**Figure 4** Comparison of PEV emissions with CV emissions: testing the importance of regional driving patterns, left: VMT pattern assigned by state level only; right: both state and urbanization level.
Figure 5 shows the results in comparison with the base case. With delayed charging, Nissan Leaf emissions increase in most regions. This is due to the fact that lower load at night implies that more inexpensive coal-fired power plants operate below capacity and are available to respond to marginal load. This is the case for all NERC regions except NPCC, where we actually see an improvement in emissions with delayed charging. The results indicate that, although nighttime charging is a more economical option for the customer, it typically results in higher CO₂ emissions.

![Leaf - Prius HEV Emissions (g/mi)](image1)

![Leaf - Prius HEV Emissions (Delayed Charging, g/mi)](image2)

**Figure 5** Leaf vs. Prius emissions comparison, testing the importance of charging scheme. Left: convenience charging, right: delayed charging

2.5. Case 4: Testing the Importance of Driving Cycle

As explained in the main text, in our base case simulations, we consider the regional differences in drive cycles (speed-time patterns) by assigning each county either a city, highway or combined driving cycle based on the county’s MSA level. To test the importance of drive cycle, we also run a case where we neglect the differences MSA levels and consider combined driving in all counties. Figure 6 summarizes the results, showing that the county-by-county variation observed in the base case is replaced by a smoother regional distribution of emissions estimates when variation in drive cycle is ignored. Of course, in practice drive cycle is heterogeneous within each county, so the assignments of drive cycle based on urbanization level in the base case serve more to highlight this difference than to identify precise differences in emissions at county boundaries.
3. Emissions Per Vehicle

Figure 7 shows the CO₂ emissions in tons per vehicle per year, i.e. it shows how many tons of CO₂ emissions an average vehicle in each county creates over a year, for all the five vehicle models considered in this study. The results are obtained from the Case 2 scenario described in Table 1 and highlights the additional emissions produced in areas with high VMT per vehicle.

The CO₂ emissions per vehicle due to electricity consumption is estimated as follows:

$$
\zeta_{jl}^{ELEC} = \frac{\sum_{d}\sum_{h} r_{j}^{CHG} (E_{ldh}^{MEF} + E_{ldh}^{UPST})}{10^6 V_{l}} \quad \forall j, l \in L
$$

(16)

where $\zeta_{jl}^{ELEC}$ is the CO₂ emissions due to electricity consumption in tons/vehicle/year and $V_{l}$ is the number of vehicle profiles at location $l$. Similarly, due to gasoline consumption:

$$
\zeta_{jl}^{GAS} = \frac{\sum_{d}\sum_{h} (G_{ldh}^{COMB} + G_{ldh}^{UPST})}{10^6 V_{l}} \quad \forall j, l \in L
$$

(17)

where $\zeta_{jl}^{GAS}$ is the CO₂ emissions due to gasoline consumption in tons/vehicle/year. Then, total emissions per vehicle $\zeta_{jl}$ in each location $l$ over a year is estimated as:

$$
\zeta_{jl} = \zeta_{jl}^{ELEC} + \zeta_{jl}^{GAS} \quad \forall j, l \in L
$$

(18)

Note that, this comparison of per vehicle CO₂ emissions can be misleading for the Nissan Leaf BEV, since the total miles driven by the Nissan Leaf is not equal to the total miles driven for other vehicles. As explained in Section 1, in our analysis if the distance driven in a vehicle profile is longer than the AER of
the BEV, we assume the BEV shortens travel on those days. Therefore, a per mile base reporting provides a more fair comparison when the BEV is involved. In addition, in states like Wyoming where the number of vehicle profiles that match the county’s urbanization level can be as few as 30 vehicles, the distribution of VMT is a relatively coarse approximation, and results can be sensitive to random variation.

Figure 7 Estimated CO₂ emissions per vehicle in each county over a year in tons. The Nissan Leaf BEV assumes truncated VMT patterns due to the vehicle’s limited range, resulting in lower emissions per vehicle.
4. Additional Description of the Data Used

We combine various sets of data in this study to assess the emission benefits of vehicle electrification. These data sets were explained in the main text. Table 2 provides a summary of the data sets, giving the source and temporal and spatial resolution for each.

| Parameter                                               | Source                                                                 | Spatial Resolution | Time Resolution |
|---------------------------------------------------------|------------------------------------------------------------------------|--------------------|-----------------|
| Energy consumption rate as a function of temperature    | Argonne Downloadable Dynamometer Dataset                               | N/A                | N/A             |
| Climate (ambient temperature)                           | NREL Typical Meteorological Year Database (TMY)                        | 1011 locations across the country<sup>a</sup> | Hourly          |
| Daily VMT and driving times                             | NHTS                                                                   |                     | Daily           |
| Urbanization Level                                      | Tamayo et al. 2015<sup>2</sup>                                         | County             | N/A             |
| MSA Level                                               | Tamayo et al. 2015<sup>2</sup>                                         | County             | N/A             |
| Electricity emission factors (MEFs)                    | Siler-Evans et al. 2012<sup>3</sup>                                    | NERC regions       | Hourly          |
| Electricity upstream emissions per unit output for coal and gas plants | Tamayo et al.<sup>2</sup> (estimated based on Siler-Evans et al. 2012<sup>3</sup>, Graff Zivin et al. 2014<sup>4</sup>, Venkatesh et al. 2011<sup>5</sup>, Venkatesh et al. 2011<sup>5</sup>, and U.S. EPA 2009<sup>6</sup>) | NERC Regions       | Hourly          |
| Gasoline combustion                                     | Average of values from EPA 2014<sup>7</sup> and Venkatesh et al. 2011<sup>4</sup> | Country (U.S.)     | N/A             |
| Gasoline production and transportation                  | Average of values from Venkatesh et al. 2011<sup>4</sup> and GREET 2013<sup>8</sup> | Country (U.S.)     | N/A             |

4.1. Argonne D3 Database

Table 3 2013 Chevy Volt Fuel Consumption and Battery Energy Consumption for City and Highway

| Charge Depleting (CD) Mode | Fuel consumption [gal/mi] | Battery energy [ft] | CITY | 72 F | 95 F | 20 F | 72 F | 95 F | HIGHWAY | 72 F | 95 F |
|----------------------------|---------------------------|---------------------|------|------|------|------|------|------|---------|------|------|
|                            |                           |                     | 20 F |      |      |      |      |      | 20 F    |      |      |
|                            |                           |                     |      |      |      |      |      |      |         |      |      |
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|                            |                           |                     |      |      |      |      |      |      |         |      |      |

<sup>a</sup> extrapolated for 3109 counties in continental US in the simulations
| Charge Sustaining (CS Mode) | Fuel consumption [gal/mi] | Battery energy consumption [Wh/mi] |
|---------------------------|--------------------------|----------------------------------|
|                           | 0.030                    | -                                |
|                           | 0.023                    | -                                |
|                           | 0.032                    | -                                |
|                           | 0.020                    | -                                |
|                           | 0.020                    | -                                |
|                           | 0.024                    | -                                |

**Figure 8** Comparison of electricity consumption of Leaf, Volt and Prius PHEV, in Wh/mi.

Volt and Prius PHEV at Charge Depleting Mode.

**Figure 9** Comparison of gasoline consumption (gal/mi)

### 4.2. Electricity Emission Factors

Electricity marginal and upstream emission factors used in this study are given in Figure 10. Gasoline combustion and upstream emission factors are provided in Table 4.
Figure 10 Electricity use and upstream emission factors used in the study

Table 4 Gasoline emissions factors used in the study

|                  |                 |
|------------------|-----------------|
| Gasoline Combustion | 8655 g CO₂/gal |
| Gasoline Upstream       | 2400 g CO₂/gal |
5. Effect of hot temperatures on Leaf emissions

As can be seen from Figure 3 in the main text, the emissions in CA and AZ are very similar in the base case – in fact the emissions in AZ are slightly lower. This is surprising, considering the counties selected in CA are from a mild climate region, whereas AZ has extreme hot days, and Yuksel and Michalek 2015 suggested that the emissions in AZ were about 22% higher than the emissions in Northern CA. Although these results seem contradictory, this is primarily due to the different vehicle efficiency data used in two studies. Figure 11 gives the comparison between the data used in two studies.

![Nissan Leaf Energy Consumption per mile](image-url)

**Figure 11** Nissan Leaf energy consumption from different data sources and at different drive cycles

In the FleetCarma data used in Yuksel and Michalek 2015, the energy consumption per mile is always higher than the Argonne test results (for city, highway and combined drive cycles). This is expected, since FleetCarma data is real world data, and it therefore contains some effects due to different driving styles, trip conditions, such as congestion, driver preferences on climate control, vehicle differences such as the model year, and other weather-related elements, such as precipitation, humidity, and traffic. Further, real world driving conditions are expected to be more energy consuming than UDDS and HWFET tests. Our results, based on laboratory tests, are thus optimistic for all vehicles relative to real world conditions.

In addition, we see that in the FleetCarma data, the energy consumption at 95°F is approximately as high as the energy consumption at 20°F. However, in Argonne test results, we see that energy consumption at 95°F is only 70% of the energy consumption at 20°F. Argonne tests at 95°F are performed by running the
A/C enough to maintain cabin temperature at 72F. In on-road conditions, drivers may operate A/C differently, and the A/C may experience different loading due to differences in convective heat transfer.

To show how much the results would change if FleetCarma data is used in this analysis, we repeat the simulations using FleetCarma data and compare it to the Nissan Leaf emissions using Argonne data. Two scenarios are considered when using Argonne data: (1) driving cycles are assigned to counties using urbanization level as described in the base case simulations, (2) combined driving cycle is used for all counties. The FleetCarma data does not differentiate drive cycles. Figure 12 shows the difference between the results obtained by FleetCarma and Argonne data in grams/mile. As depicted from the figure, the difference is highest in the hot regions, but it is also high in cold climate regions. The reason for that is, FleetCarma data involves data points for temperatures as low as -15F and energy consumption increases for low temperatures. In the Argonne data, the minimum temperature record is at 20F, and below that temperature we assume the energy consumption is the same as its value at 20F. Therefore, the difference between two data sets increases as temperature decreases below 20F.

![Figure 12](image)

**Figure 12** CO$_2$ emissions in gram/mile: Results with Argonne data subtracted from the results with FleetCarma data. In Map (a), when using Argonne data, county level drive cycles are based on urbanization level. Whereas in map (b), combined driving cycle is used for all counties.

6. **Extrapolating Energy Consumption Data**

In our simulations, we assumed whenever the temperature is below or above the boundaries of the data (i.e. below 20F and above 95F), the energy consumption is the same as at the respective boundary. To test the effect of this assumption, we repeat the simulations for Nissan Leaf and Prius HEV by linearly extrapolating the data points beyond the boundaries. The difference in the two data assumptions for the
Nissan Leaf is shown in Figure 13, and the comparison of the results is provided in Figure 14. We see that the difference due to extrapolation change net results very little.

**Figure 13** Nissan Leaf Argonne and FleetCarma Data-Comparison with and without extrapolation of Argonne data

**Figure 14** Leaf vs. Prius emissions comparison, testing the effect of extrapolating data points beyond the boundaries. Left: base case, right: results with data extrapolated.
7. U.S. County Urbanization Level

![Map of US counties color-coded with respect to their MSA levels. Yellow: nonmetropolitan (highway driving), gray: central (city driving), green: outlying (combined driving).](image)

**Figure 15** US counties color-coded with respect to their MSA levels – yellow: nonmetropolitan (highway driving), gray: central (city driving), green: outlying (combined driving)

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