Climate and Air Quality Impacts of Electric Vehicles and Comparison to U.S. Tax Credits

by

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ABSTRACT

Road transportation is the largest contributor to CO_2 and second largest contributor to early deaths from air pollution in the U.S. To decarbonize and meet its contribution to the Paris Agreement goal of global average temperature rise <2°C and curb human health impacts from air quality, the U.S. must reduce its road sector emissions. Electrification of the light duty vehicle fleet is a potential solution, and the federal government is offering a $7,500 tax credit, along with 15 states with up to $5,000 rebates on battery electric vehicle (BEV) purchases. This study compares the monetized climate and air quality impacts of driving a BEV over a gasoline internal combustion engine vehicle (ICEV) for its full useful life to the federal and state subsidies in the 48 contiguous states. This comparison is an indicator of how well matched the subsidies are to the potential benefits. I use driving patterns across urban, suburban, and rural regions in addition to ICEV and BEV emission factors to compile an emissions inventory across vehicle sizes, trims, and model years. I convert the air pollution emissions to early deaths using new mortality scaling factors calculated from previous work. I determine the monetized climate impacts using the social cost of carbon, and the air quality impacts using mean value of a statistical life. I find that for a new base trim non-luxury compact SUV, the BEV is on average a $1,212 benefit for climate in 46 states, $1,555 benefit for air quality in 32 states, and a combined average of $2,391 benefit in 42 states. The climate and air quality benefit is smaller than the federal and state subsidy in all states by an average of $6,320, except in New Jersey where the benefit is larger by $30. In states where there are BEV damages over an ICEV, no state subsidy is offered. I find that the average combined BEV benefit is positive in all states and 3.8 times larger for a top trim large luxury sedan than a base trim non-luxury compact SUV, due to minimal efficiency penalties for higher performance from upgrading to top trims for BEVs compared to ICEVs. I also find that ammonia (NH_3) dominates the total damages, contributing to 56% and 37% for ICEVs and BEVs, respectively, in Massachusetts for example. Three-way catalytic converters (TWC) in gasoline ICEVs produce NH_3, while selective catalytic reduction (SCR) used in power plants exhibit ammonia slip, both of which reduce nitrogen oxides (NO_x). The northeast and west coast states have higher benefits while midwestern states have smaller benefits or damages from BEVs. Careful evaluation is needed to avoid climate and air quality damages from BEVs when considering expansion and/or extension of the federal subsidy due to regional disparities in emissions of the electric grid. This highlights the importance of emissions reduction from the electric grid along with vehicle fleet electrification.

Thesis Supervisor: Steven R. H. Barrett
Title: Professor of Aeronautics and Astronautics

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1. Introduction

1.1 Role of transportation in climate and air quality impacts

Reduction of greenhouse gas emissions (GHGs) is critical to meet the Paris Agreement climate goals to curb the rise in average global temperature to below 2°C [1]. The US emitted 15% of carbon dioxide (CO_2) globally in 2019 [2], 29% of which was from transportation, the largest contributor, followed by 25% from electricity [3]. Within transportation, the largest proportion belonged to light duty vehicles at 58%, and thus reduction of GHGs from light duty vehicles and the electricity sectors in the US is required to meet federal economy-wide climate reduction goals such as the 50–52% reduction in greenhouse gas pollution by 2030 from 2005 levels set forth by President Biden this year [4].

Air pollution from road transport lead to 18,356 premature mortalities in the US in 2018 according to Dedoussi et al. [5] which was 24% of early deaths from all sectors, the second largest contributor after residential use such as biomass burning. The power generation sector was the 4th largest contributor and caused 8,470 deaths or 11% of all premature mortalities. The main pollutants which cause early deaths are fine particulate matter with a diameter of 2.5μm or less ($PM_{2.5}$) and ozone (O_3). $PM_{2.5}$ can be emitted directly from car exhausts and power plants, as well as formed from gaseous precursor chemicals, including nitrogen oxides (NO_x), sulfur oxides (SO_x), and ammonia (NH_3), while O_3 is formed from NO_x and volatile organic compounds (VOCs) reacting under sunlight [6]. Once inhaled, $PM_{2.5}$ can travel to the lungs and throughout the bloodstream, causing premature mortalities in those with heart or lung disease [7], and is also the main source of reduced visibility from haze [8]. O_3 exposure also leads to early deaths from cardiovascular and respiratory diseases and is the main ingredient in smog [9]. Thus, significantly reducing human health impacts from air pollution will require reductions in precursor and direct (primary) $PM_{2.5}$ emissions from the road and electric sectors in the US.

Electrification of the light duty vehicle fleet in the US is seen as part of the solution to both climate and air quality (AQ) problems, and thus the federal government and 15 states have adopted a subsidy program to boost sales of battery electric vehicles (BEVs) and gradually replace the internal combustion engine vehicle (ICEV) fleet.

1.2 Literature review, research question, novelty of study

The literature on calculation of climate and air quality impacts of BEVs is extensive, but none, to the best of my knowledge, compares the monetized impacts to federal and state subsidies. Choma et al. [10] assesses only health impacts, ignores O_3 and powerplant emissions of NH_3 and VOCs, and does not compare to subsidies. Holland et al. (2016) [11] is the closest to this study, by calculating both monetized climate and air quality impacts and providing a comparison to federal subsidies. However, state subsidies are not considered as most did not exist at the time of publication, and the analysis does not include NH_3 emissions which I find in this study to be the dominant pollutant for environmental damages. Holland et al. (2016) also does not take into account differences in $PM_{2.5}$ from brakewear due to regenerative braking in BEVs and uses the AP2 model for air quality damages. Holland et al. (2019) [12] focuses on income and ethnic group differences of air quality exposure, while Holland et al. (2020) [13] does not take into account VOCs and NH_3, nor the state subsidies. Nopmongcol et al. [14] focuses on future scenarios for air quality damages only, while Kamiya et al. [15] focuses on climate impact only. Tong and Azevedo [16] calculate both climate and air quality damages but do not compare damages to the subsidies.

The main research questions to be answered are: what are the monetized climate and air quality impacts of driving a BEV over an ICEV for its full useful life by US state? How do they compare to the federal and state subsidies?

This study calculates damages from CO_2, NO_x, SO_2, $PM_{2.5}$, NH_3, and VOCs for both ICEVs and BEVs. For air quality pollutants, I use mortality scaling factors derived from Dedoussi et al. [5] which used GEOS-Chem Adjoint, a chemistry transport model. I include sensitivities across all vehicle size classes, non-luxury and luxury, base and top trims, and model years available at the time of writing for fair comparisons between BEVs and ICEVs. The emissions for the electric grid are matched to the closest available data for the vehicle model year considered, and the sensitivity to state average vs NERC region dispatch model emissions are included. Climate, air quality, and combined damages are shown separately for both ICEVs and BEVs, as well as the respective BEV benefits. The combined BEV benefits are compared to the combined federal and state subsidies, taking into account varying eligibility and amounts according to vehicle price, income level, and model year of vehicle for each state. Studies have not addressed some of these elements and no study exists which combines all of these elements into an integrated assessment.

2. Methods

To compare the climate and air quality impact of driving a gasoline ICEV to that of a BEV for its full useful life, I first use information on driving patterns across urban, suburban, and rural regions in the U.S. This is combined with ICEV emission factors and BEV emission factors derived from vehicle efficiency and power plant emissions to compile an emissions inventory across vehicle sizes, trims, and model years. I convert the air pollution emissions to early deaths using new mortality scaling factors calculated from previous work. I determine the monetized climate impacts using the social cost of carbon, and the air quality impacts using mean value of a statistical life. The impacts are then compared by state to the federal and state subsidies.

2.1 Annual miles traveled by region

The national average distance driven is 11,104 miles from the Bureau of Transportation Statistics Local Area Transportation Characteristics for Households (2017 BTS LATCH survey) [17]. These miles traveled are apportioned to each type of region in the state. I divide each state into urban, suburban, and rural regions based upon population density divisions determined from LATCH. These regions are spatially assigned to census tracts for each state using the 2017 shapefile Topographically Integrated Geographic Encoding and Referencing (TIGER) database [18] and ArcGIS Pro software version 2.8.1. Massachusetts is shown as an example in the Appendix. More recent versions of census tracts shapefiles are available, but the urban, suburban, rural regional division required in this study could only be found from BTS LATCH, thus I match everything to 2017 for consistency. I then overlay the 2017 national road network geodatabase from TIGER [19] on top of the census tract shapefile with urban/suburban/rural regional divisions to attain the regionally classed road network. I calculate the length of each road segment then sum by region to get the total length by TIGER road classification. Next, the Highway Performance Monitoring System (HPMS) publishes Vehicle-Miles Traveled (VMT) data by state each year (table VM-2 for 2017) [20] that can be used to apportion the annual miles to different regions, but only divides by urban and rural, and uses more divisions (Federal Functional Class) of road classifications than TIGER. Table 1 matches road classifications across TIGER and HPMS, partially following Gately et al. [21], and EPA MOVES, required for later use with drive cycles [22]. I calculate the urban and suburban TIGER road lengths via scaling by the ratio of HPMS urban road lengths to the sum of TIGER urban and suburban road lengths, as shown in equations 1 and 2. This is repeated for secondary and local road types. HPMS road lengths are from Table HM-20 from 2017 [23]. I found that census urban areas and clusters used in the HPMS definition of urban generally groups together the urban and suburban areas defined by BTS LATCH while leaving the rural areas intact, thus the HPMS urban areas are matched to the TIGER urban and suburban regions.

Table 1 – Road type assignment between HPMS Federal Functional Class and TIGER roads

<table>
<tr><th>HPMS Road Type</th><th>TIGER Road Type</th><th>EPA MOVES Road Type</th></tr>
<tr><td>1: Interstate</td><td rowspan="3">S1100: Primary</td><td rowspan="3">Restricted</td></tr>
<tr><td>2: Principal Arterial – Freeways & Expressways</td></tr>
<tr><td>3: Principal Arterial – Other</td></tr>
<tr><td>4: Minor Arterial</td><td rowspan="2">S1200: Secondary</td><td rowspan="4">Unrestricted</td></tr>
<tr><td>5: Major Collector</td></tr>
<tr><td>6: Minor Collector</td><td rowspan="2">S1400: Local</td></tr>
<tr><td>7: Local</td></tr>
</table>

$$\sum RL_{urban,S1100} = \sum TIGER\ RL_{urban,S1100} \times \frac{\sum HPMS\ RL_{urban,S1100}}{\sum TIGER\ RL_{urban+suburban,S1100}} \quad (1)$$

$$\sum RL_{suburban,S1100} = \sum TIGER\ RL_{suburban,S1100} \times \frac{\sum HPMS\ RL_{urban,S1100}}{\sum TIGER\ RL_{urban+suburban,S1100}} \quad (2)$$

The total road lengths in TIGER are larger than what are reported in HPMS HM-20 due to HPMS being a highway monitoring system, and not including many smaller roads. Since HPMS VM-2 VMT is based upon HM-20 road lengths, all TIGER road lengths are scaled to HPMS road lengths. The secondary and local road lengths are aggregated to unrestricted road lengths across regions, while primary road lengths are considered restricted road lengths. VMT is defined in equation 3, where AADT is annual average daily traffic based on traffic counts, cameras, and estimations in one road segment and RL is the road length of the segment.

$$VMT = \sum AADT\ [vehicles] \times RL\ [mi] \times 365\ \frac{days}{year} \quad (3)$$

$$VMT_{urban,restricted} = HPMS\ VMT_{urban,restricted} \times \frac{\sum TIGER\ RL_{urban,restricted}}{\sum TIGER\ RL_{urban+suburban,restricted}} \quad (4)$$

$$VMT_{suburban,restricted} = HPMS\ VMT_{urban,restricted} \times \frac{\sum TIGER\ RL_{suburban,restricted}}{\sum TIGER\ RL_{urban+suburban,restricted}} \quad (5)$$

The VMT for urban and suburban regions and restricted, unrestricted road types are scaled by road lengths as in equations 4 and 5, while rural VMT is taken directly from HPMS VM-2. Finally, the annual miles driven for each region and road type are scaled by VMT as in equation 6.

$$Annual\ Miles_{urban,restricted} = Annual\ Miles_{total} \times \frac{VMT_{urban,restricted}}{VMT_{total}} \quad (6)$$

2.2 Vehicles

The vehicles configurations used are shown below in Table 2. Every vehicle class that is available for sale with published EPA fuel economy ratings for BEVs is represented with a comparable ICEV model [24]. The oldest and newest of each class, and some with model years in between, are used to show progression of damages over the past 2 years, for categories still in its infancy like the luxury compact SUV, to the past decade like the compact. The best selling vehicle of each type for BEVs is chosen, and the comparable best-selling ICEV model is chosen by similar size class [25]. If this is not obvious, such as in the case of the Tesla Model S, where journalists disagree on whether to class it as a mid or large size luxury sedan, the EPA interior volume is used and the closer class to which the ICEV belongs is chosen [26].

Table 2 – Vehicle configurations used

Class	**Type**	**Year**	**Model**	**Trim**
Compact	ICEV	2011	Nissan Versa 1.6 5-speed	Base
	BEV		Nissan Leaf	
	ICEV		Nissan Versa 1.8 CVT	Top
	BEV		Nissan Leaf	
	ICEV	2021	Nissan Versa 5-speed	Base
	BEV		Nissan Leaf 40kWh	
	ICEV		Nissan Versa CVT	Top
	BEV		Nissan Leaf 60kWh	
Compact SUV	ICEV	2019	Hyundai Kona 2.0L FWD	Base
	BEV		Hyundai Kona EV	
	ICEV		Hyundai Kona 1.6T FWD	Top
	BEV		Hyundai Kona EV	
	ICEV	2022	Hyundai Kona 2.0L FWD	Base
	BEV	2021	Hyundai Kona EV	
	ICEV	2022	Hyundai Kona 1.6T FWD	Top
	BEV	2021	Hyundai Kona EV	
Compact Luxury SUV	ICEV	2021	BMW X3 sDrive30i / Audi Q5	Base
	BEV		Tesla Model Y Standard Range / Audi e-tron	
	ICEV		BMW X3 M / Audi SQ5	Top
	BEV		Tesla Model Y / Audi e-tron	

Class	Type	Year	Model	Trim
Mid-Size Luxury SUV	ICEV	2017	BMW X5 xDrive35i / Lexus RX 350 AWD	Base
	BEV	2016	Tesla Model X 60D	
	ICEV	2017	BMW X5 M	Top
	BEV	2016	Tesla Model X P100D	
	ICEV	2019	BMW X5 xDrive40i/Lexus RX 350L AWD	Base
	BEV	2018	Tesla Model X 75D	
	ICEV	2020	BMW X5 M	Top
	BEV	2018	Tesla Model X P100D	
	ICEV	2020	BMW X5 xDrive40i	Base
	BEV	2019	Tesla Model X 75D	
	ICEV	2020	BMW X5 M	Top
	BEV	2019	Tesla Model X Performance (22” wheels)	
	ICEV	2021	BMW X5 xDrive40i	Base
	BEV	2020	Tesla Model X Standard Range	
	ICEV	2021	BMW X5 M	Top
	BEV	2021	Tesla Model X Performance (20” wheels)	
Compact Luxury Sedan	ICEV	2019	BMW 330i	Base
	BEV	2018	Tesla Model 3 Mid Range	
	ICEV	2018	BMW M3	Top
	BEV		Tesla Model 3 LR AWD Performance	
	ICEV	2020	BMW 330i	Base
	BEV	2019	Tesla Model 3 Standard Range	
	ICEV	2021	BMW M3	Top
	BEV	2019	Tesla Model 3 LR AWD Performance	
	ICEV	2021	BMW 330i	Base
	BEV		Tesla Model 3 Standard Range Plus	
	ICEV		BMW M3	Top
	BEV		Tesla Model 3 Performance	
Large Luxury Sedan	ICEV	2012	Tesla Model S	Base
	BEV		Mercedes-Benz S550	
	ICEV		Tesla Model S	Top
	BEV		Mercedes-Benz S65 AMG	
	ICEV	2019	Mercedes-Benz S450	Base
	BEV	2018	Tesla Model S 75kWh	
	ICEV	2019	Mercedes-Benz S65 AMG	Top
	BEV	2018	Tesla Model S P100D	
	ICEV	2020	Mercedes-Benz S560 4Matic	Base
	BEV	2019	Tesla Model S Standard Range	
	ICEV	2020	Mercedes-Benz S65 AMG	Top
	BEV	2019	Tesla Model S Performance (19” wheels)	
	ICEV	2020	Mercedes-Benz S560 4Matic	Base
	BEV		Tesla Model S Standard Range	
	ICEV	2020	Mercedes-Benz S65 AMG	Top
	BEV	2021	Tesla Model S Performance (19” wheels)	

In choosing matching trim levels for BEVs and ICEVs, the least and most expensive trims as well as matching power outputs are considered. The same model year between ICEVs and BEVs is not always used, as the industry generally names its model years one year into the future from the year the vehicle is actually released (2022 vehicles are available now in 2021), while Tesla, for example, does not follow this practice. Sometimes a newer or older vehicle is used as models at the base or top trims disappear and reappear for both BEVs and ICEVs, although this in itself is of note when discussing model year progressions. When more than one vehicle is displayed for a class, both vehicles were used. The Lexus RX 350 is the sales leader in the mid-size SUV category, but the BMW X3 is the sales leader in the compact luxury SUV class, so to maintain continuity in making comparisons between the two classes, the BMW X5 is also calculated. The Audi e-tron is used in addition to the Tesla Model Y, as the Tesla does not qualify for the federal subsidy due to the manufacturer's expired credits after 200,000 units sold. When showing differences between climate and air quality benefits of a BEV and subsidies, the Audi is used as it does qualify for the federal subsidy.

2.3 Gasoline vehicle emissions

The drive cycle assignment to road types is shown in Table 3. Restricted roadways are restricted access, meaning an on ramp is required to enter the road, so they are generally interstates and highways as previously shown in Table 1. Unrestricted roadways have stop signs, traffic lights, or nothing that restricts access to the road, so these are all other roads that are not restricted, including local. From this point forward, restricted roads are referred to as highways and unrestricted roads are referred to as local for ease of understanding for the reader.

Table 3 – Drive cycle assignment by road

Region and Road	**EPA drive cycle**	**Substantiation for climate**
Urban Highway	Highway	MOVES shows similar CO_2 for highways [27]
Urban Local	City	Yuksel et al. (2016) [28]
Suburban Highway	Highway	MOVES shows similar CO_2 for highways
Suburban Local	Combined	Yuksel et al. (2016)
Rural Highway	Highway	Barrett et al. (2015) [29], Yuksel et al. (2016)
Rural Local	Highway	MOVES shows similar rural CO_2 [27]

Substantiations shown in table 3 based on CO_2 are assumed to be also valid for calculating air quality impacts, thus the same drive cycle to region and road assignments are used throughout the analysis. The EPA MOtor Vehicle Emission Simulator (MOVES3) software shows that the average passenger car in 2021 in the U.S. emits 215gCO_2/mi across urban and rural highways, and 217gCO_2/mi in rural local roads, thus the highway cycle is chosen for all highways and all rural roads. Yuksel et al., which studied CO_2 emissions of BEVs, chose the city cycle for all urban driving, combined cycle for all suburban driving, and highway driving for all rural roads, as they do not distinguish among road types. Barrett et al. also assigns rural highway driving to the highway cycle. The combined cycle for fuel economy is a weighted average of 55% city and 45% highway driving. EPA drive cycle refers to the fuel economy guide cycles, which are calculated from a combination of the individual test cycles including Federal Test Procedure (FTP) for urban driving, HFET (Highway Fuel Economy Test), US06 (Supplemental

FTP) for aggressive highway driving, SC03 (Speed Correction) for driving with air conditioning, and Cold FTP for urban driving in cold weather. CO_2 emission factors for each vehicle model are obtained from the EPA fuel economy guide [30].

For NO_x and VOCs, I use the EPA Tier 3 pollutant limits which regulate NO_x+NMOG (Non-Methane Organic Gases) [31]. All factors are in grams per mile unless otherwise noted. These limits must be met up to 150,000 miles on both the FTP and HFET cycles. The full useful life of a vehicle is 173,151 miles driven for an average passenger car from The Greenhouse Gases, Regulated Emissions, and Energy use in Technologies model (GREET 2020) [32], and I assume the EPA Tier 3 limits apply to this mileage. NMOG is taken to be equivalent to VOCs as assumed in Holland et al. (2016) [11]. To isolate the NO_x and VOCs to separately calculate their damages, I use ratios of NO_x and VOCs to NO_x+VOCs for urban and rural highway and local roads from EPA MOVES [27] for passenger cars and light trucks for their respective model years in equations 7 and 8. The suburban highway NO_x is assumed to be the same as that for urban highways as was done for CO_2, based on the assumption that NO_x scales with fuel economy as done in Chossiere et al., [33] and since CO_2 is directly proportional to fuel economy. For suburban local roads, equation 9 is used, on the same basis of NO_x scaling with fuel economy, and following the EPA combined fuel economy method. Equation 9 also applies for VOCs. Units are shown in brackets.

$$NO_x\left[\frac{g}{mi}\right] = (NO_x + NMOG)_{Tier\ 3} \times \left(\frac{NO_x}{NO_x + VOC}\right)_{MOVES} \tag{7}$$

$$VOC\ \left[\frac{g}{mi}\right] = (NO_x + NMOG)_{Tier\ 3} \times \left(\frac{VOC}{NO_x + VOC}\right)_{MOVES} \tag{8}$$

$$NO_{x,suburban\ highway}\left[\frac{g}{mi}\right] = .55 \times NO_{x,urban\ local} + .45 \times NO_{x,rural\ local} \tag{9}$$

For direct (primary) $PM_{2.5}$ from vehicle exhaust, I use the average of the certification limit and in-use limit in EPA Tier 3 [31], which is the same value for all bins except bin 0 (zero emission vehicles). The in-use value is higher as the manufacturer reports emission test values for vehicles with mileage from 2,000 to 871,300, and the EPA also randomly recruits customer owned used vehicles for testing to verify data from the manufacturer. The certification limit is 3mg/mi, the in-use limit is 6mg/mi, and the average of 4.5mg/mi is used to account for vehicle aging as the full useful life of a passenger car is 15.6 years of driving at 11,104 miles per year. I assume the exhaust $PM_{2.5}$ is uniform across road types and regions. The brakewear and tirewear $PM_{2.5}$ from EPA MOVES [27] is added separately to urban highways as shown in equation 10 and repeated for other road types, while all suburban roads follow the urban emission factors.

$$PM_{2.5,Total,Urban,Highway} = \frac{PM_{2.5,Cert} + PM_{2.5,InUse}}{2} + \left(PM_{2.5,Brake} + PM_{2.5,Tire}\right)_{Urban,Highway} \tag{10}$$

Sulfur dioxide (SO_2) emissions scale with fuel economy [11] as they are a function of sulfur content in the fuel. I use the ratio of SO_2 to CO_2 emissions, which is proportional to fuel consumption, from EPA MOVES [27] for the respective model year and passenger car or light truck for each road type and region, then scale with the CO_2 for the specific vehicle model from

EPA fuel economy (FE) guide data [30] to find the SO_2 for each vehicle model for each type of road. The urban highway case is shown in equation 11 and repeated for other regions and road types, and I assume the ratios for suburban driving are the same as for urban driving.

$$SO_{2,Urban,Highway}\left[\frac{g}{mi}\right] = \left(\frac{SO_2}{CO_2}\right)_{Urban,Highway,MOVES} \times CO_{2,Urban,Highway,EPA\,FE} \tag{11}$$

I assume ammonia emissions scale by CO_2, i.e. fuel consumption, as Sun et al. [34] shows NH_3/CO_2 ratios are useful for ammonia estimation, and Farren et al. [35] uses a top-down approach with fuel consumption to calculate CO_2, then uses NH_3/CO_2 ratios to determine total NH_3 emissions. Equation 12 is used to calculate NH_3 emissions.

$$NH_{3,Urban,Highway}\left[\frac{g}{mi}\right] = \left(\frac{NH_3}{CO_2}\right)_{Urban,Highway,MOVES} \times CO_{2,Urban,Highway,EPA\,FE} \tag{12}$$

It is understood that ammonia is not a direct product of combustion, but of the operation of the three-way catalytic converter (TWC) in gasoline vehicles. The water-gas shift reaction produces hydrogen gas and carbon dioxide as shown in equation 13 from carbon monoxide and water, which are a few of the many products of combustion. Then, the hydrogen gas reacts with

$$CO + H_2O \rightarrow CO_2 + H_2 \tag{13}$$

nitric oxide produced from combustion and catalytic reduction of NO_2, by two pathways [86] as shown in equations 14 and 15.

$$2NO + 2CO + 3H_2 \rightarrow 2NH_3 + 2CO_2 \tag{14}$$

$$2NO + 5H_2 \rightarrow 2NH_3 + 2H_2O \tag{15}$$

Finally, I note that on-road, in-use emissions may vary from (but not necessarily be higher than) EPA Tier 3 emission limits which are met in laboratory testing, in light of the Volkswagen diesel emissions scandal in 2015. In response, the EPA now conducts random real-world tests outside of the laboratory on both diesel and gasoline models to confirm compliance [36, 37]. In addition, unlike diesel, a DOT report suggests EPA MOVES may overestimate NO_x emissions by up to 738% compared to on road measurements for gasoline vehicles [38].

Each emissions factor (EF) is multiplied by the miles driven by region and road type and summed to calculate the total emissions by pollutant. This is multiplied by 15.6 years to cover the 173,151 miles full useful life distance at 11,104 miles per year. This assumes that there is no change in emissions from vehicle aging and that annual distance driven is constant for 15.6 years. While EFs are assumed to be a national constant, the proportion of urban, suburban, and rural driving varies by state. An example for annual NO_x on urban highways in Massachusetts is shown in equation 16.

$$NO_x\,[g] = NO_{x,Urban,Highway}\left[\frac{g}{mi}\right] \times annual\ miles_{Urban,Highway,MA} \times 15.6\frac{years}{vehicle\ life} \tag{16}$$

This total emission is then multiplied by mortality scaling factors shown in section 2.6.

2.4 Electric vehicle emissions

For all emissions, the state average grid emissions factor is used. This is calculated by equation 17 for all pollutants. The net generation comes from EIA annual generation tables [39] matched to respective model year of the vehicle, CO_2, NO_x, SO_x emissions are from EIA annual emissions tables [40], and $PM_{2.5}$ from powerplants, VOC, and NH_3 emissions come from the National Emissions Inventory (NEI) 2011 [41], 2018 projection [42] and 2017 for electric generation [43].

$$CO_2, NO_x, SO_2, PM_{2.5,Power}, VOC, NH_3 \left[\frac{g}{kWh}\right] = \frac{Total\ annual\ emission\ [g]}{Net\ annual\ generation\ [kWh]} \tag{17}$$

$$CO_2, NO_x, SO_2, PM_{2.5,Power}, VOC, NH_3\ [g] = EF \left[\frac{g}{kWh}\right] \times \frac{Energy}{year}\left[\frac{kWh}{yr}\right] \times \frac{15.6\ years}{vehicle} \tag{18}$$

$$Annual\ Energy \left[\frac{kWh}{yr}\right] = \sum \left(Efficiency \left[\frac{kWh}{mi}\right] \times \frac{miles}{year}\right)_{Urban,Rural,Highway,Local} \tag{19}$$

This is multiplied by the total annual energy use of the vehicle to obtain the annual emissions by pollutant as in equation 18. The energy use is derived from vehicle efficiencies provided in the EPA fuel economy comparison tool and converting to kWh/mi using 1 gallon of gasoline = 33.7kWh as defined by the EPA [44]. The total energy use is the sum of energies used in different road types and regions as in equation 19, since the efficiencies vary. The assignment of cycles to road types and regions is identical to ICEVs from Table 3.

I assume $PM_{2.5}$ emissions from tirewear to be identical to the ICEV by region and road type as EPA MOVES currently does not simulate values for BEVs separately. The $PM_{2.5}$ brakewear is taken to be appoximately 5% of the EPA MOVES ICEV values for each road type and region based on Hall [45], who found that the friction braking system was used only 5% of the time over the regenerative brakes in a BEV compared to an ICEV on a kinetic energy basis. Thus the total $PM_{2.5}$ annual emissions are shown in equation 20, repeated for each road type and region.

$$PM_{2.5,Total}\ [g] = PM_{2.5,Power}[g] + \left(PM_{2.5,Tires} + 0.05\ PM_{2.5,Brakes,ICEV}\right)\left[\frac{g}{mi}\right] \times 173{,}151\,\frac{miles}{year} \tag{20}$$

For the sensitivity analysis using the marginal grid, I use the simulated dispatch model emissions by NERC region, hour of day, and three seasons (summer, winter, and transition which combines spring and fall) for CO_2, NO_x, and SO_x [46]. Other pollutants were not available from the source and the state average values are maintained. The charging profile assumes the slowest Level 2 charging at 2.8kW [47] to charge the battery at constant full speed from 10% to 80%. Vehicle manufacturers typically discourage full depletion (0%) and full charging (100%) of the battery to preserve longevity. I assume charging begins at 6PM only on days where the battery is depleted to 10%, and is left to charge until 80% is reached, and there are no seasonal variations in charging behavior other than number of charges during summer defined as May to

September, winter as November to March at five months each, and transition as April and October for two months. An example charging profile for the 2021 Hyundai Kona EV is shown in the Appendix. The grid emission factor by hour and season is multiplied by the demand for that hour, which gives the emissions from that hour of charging. This is multiplied by the number of charges for the respective season in a year, resulting in the annual emissions for that season for that particular hour of day. All of these hourly emissions are then summed for the year which matches the model year of the vehicle being used and is then multiplied by the mortality scaling factors described in section 2.5. These steps are shown in equations 21–22.

$$Emissions_{hour,season}[g] = Grid\ EF_{hour,season}\left[\frac{g}{kWh}\right] \times 2.8kWh \tag{21}$$

$$\left(\frac{Emissions}{year}\right)_{hour,season}\left[\frac{g}{yr}\right] = Emissions_{hour,season} \times charges_{season} \tag{22}$$

For both gasoline and electric vehicles, an emissions factor comparison in Massachusetts is shown in the Appendix. Emission factors are uniform nationally for ICEVs, and vary for BEVs due to the varying electric grid.

Ammonia emissions from power plants are from ammonia slip, which is different from NH_3 production in TWCs. Ammonia stored in a tank is introduced into the exhaust gas and reacted on a catalyst to reduce NO_x. An example of urea as a reductant is shown in equation 23.

$$2NO + CO(NH_2)_2 + \frac{1}{2}O_2 \rightarrow 2N_2 + 2H_2O + CO_2 \tag{23}$$

If there is any unreacted ammonia after the catalytic reduction, it is released into the atmosphere, and this is referred to as ammonia slip.

2.5 Climate and air quality impact

The climate impact is calculated by multiplying the annual emissions by the social cost of carbon and discounting at 3% by year for 15.6 years. The sum of the discounted annual climate damages is the total climate damage from the vehicle. The updated Biden administration social cost of carbon is $51/metric ton of CO_2e in 2020 dollars [48]. The discounting method is shown in equation 24, where n is the number of years since today, and n = 0 refers to 2021.

$$Net\ Present\ Value\ (NPV\ \$) = \frac{Future\ Value}{(Discount\ Rate + 1)^n} \tag{24}$$

The air quality impact starts from introducing the state average mortality scaling factor (MSF) calculated from the results of Dedoussi et al. [5]. The total premature mortalities in and out of the state where the pollutant is emitted is divided by the pollutant emissions from the source state to generate a scaling factor. Emissions can be blown out of the source state boundaries from wind patterns taken into account by GEOS-Chem used in Dedoussi et al. This is calculated separately for road transport and electric generation, as the emissions from driving can be closer or farther from population centers depending upon the sector, and impacts the population weighted mean exposure in μg/m^3 to $PM_{2.5}$ and O_3. An example for road NO_x is shown in equation 25.

$$NO_x\ road\ mortality\ scaling\ factor\ \left[\frac{deaths}{gram}\right] = \frac{deaths\ in\ and\ out\ of\ state\ from\ road\ NO_x}{NO_x\ road\ emissions\ in\ state\ [g]} \tag{25}$$

A program coded in Python is adapted from Dedoussi et al. to obtain a matrix of deaths by precursor emissions and impacted state given an emission source state in 2018. The deaths are divided by the NEI 2011v1 2018 projections of emissions inventories for each state and sector, as these formed the basis for the analysis in Dedoussi et al. [42]. The precursor emissions for secondary (indirect) $PM_{2.5}$ are NO_x, SO_x, and NH_3, while those for O_3 are NO_x and VOCs. The concentration response functions (CRFs) used in Dedoussi et al. determine the early deaths caused by the population weighted mean exposure to $PM_{2.5}$ and O_3. The CRFs for $PM_{2.5}$ [49] and O_3 are from an increased risk for all-cause mortality, including diseases of the circulatory system (including diabetes), cardiovascular system, ischemic heart disease (IHD, reduction of blood supply to the heart), Dysrhythmias, heart failure, cardiac arrest, cerebrovascular disease, diabetes, respiratory disease, pneumonia and influenza, chronic obstructive pulmonary disease (COPD), and lung cancer [50]. The scaling factors are kept constant in 2018 while total annual emissions which vary with different model year vehicles are multiplied by the scaling factors to calculate the annual early deaths from each pollutant for a particular vehicle. An example for NO_x early deaths from road transport is shown in equation 26.

$$NO_x \frac{early\ deaths}{year} = NO_x\ road\ MSF\left[\frac{deaths}{g}\right] \times NO_{x,vehicle}\ emission\left[\frac{g}{year}\right] \tag{26}$$

The deaths from all pollutants are summed for total premature mortalities from a particular vehicle then monetized into damages using a U.S. specific mean value of a statistical life (VSL), following Grobler et al. [51]. VSL is an indicator of how much people are willing to pay to reduce the risk of death [52]. I perform an income-based country adjustment using an income elasticity of 1, based on GDP per capita, purchasing power parity basis [53, 54], with an output of a mean VSL equal to \$10.03MM in 2021 in 2020 dollars. The mean VSL is projected out to 2036 since the vehicle will operate for 15.6 years from today, and multiplied by the total annual premature deaths as in equation 27 to obtain the damage for each particular year. The damages for each year are then discounted by 3% as was done for the climate impact.

$$Damage_{year}[\$] = Total\ early\ deaths \times mean\ VSL_{year}\ \left[\frac{\$}{life}\right] \tag{27}$$

2.6 Federal and state subsidies

Table 4 shows the US state subsidy amounts, caps on maximum manufacturer suggested retail price (MSRP) for eligibility, caps on income, and any unique features. The data was collected from information linked by the National Conference of State Legislatures [55]. The federal subsidy is $7,500 and applies to all states [24] but is not included in Table 4. For any state where there is a tax exemption, the subsidy amount is based upon a $38,565 MSRP, including destination, for the 2021 Hyundai Kona EV [56]. Any state missing from Table 4 does not have a state subsidy at the time of writing. Rhode Island, for example, had a program that expired in 2017 due to lack of funding [57], the most common challenge noted across all states that did or do offer subsidies in running their programs.

Table 4 – US state subsidies, MSRP and income caps in 2020–2021 ($)

<table>
<tr><th>State</th><th>Subsidy</th><th>MSRP Cap</th><th>Income Cap</th><th>Type</th><th>Notes</th></tr>
<tr><td>California</td><td>2,000</td><td>60,000</td><td>150,000</td><td>Rebate</td><td>income cap for singles</td></tr>
<tr><td>Colorado</td><td>2,500</td><td>None</td><td rowspan="12">None</td><td>Credit</td><td>can apply to your tax return</td></tr>
<tr><td>Connecticut</td><td>2,250</td><td>42,000</td><td rowspan="2">Rebate</td><td></td></tr>
<tr><td>Delaware</td><td>2,500</td><td>60,000</td><td></td></tr>
<tr><td>Louisiana</td><td>2,500</td><td>None</td><td>Credit</td><td>10% or $2,500 whichever is smaller</td></tr>
<tr><td>Maine</td><td>2,000</td><td>50,000</td><td>Rebate</td><td></td></tr>
<tr><td>Maryland</td><td>2,314</td><td>63,000</td><td>Credit</td><td>6% or $3,000 whichever is smaller</td></tr>
<tr><td>Massachusetts</td><td>2,500</td><td>50,000</td><td rowspan="7">Rebate</td><td></td></tr>
<tr><td>New Jersey</td><td>5,000</td><td>55,000</td><td></td></tr>
<tr><td>New York</td><td>2,000</td><td>42,000</td><td></td></tr>
<tr><td>Oregon</td><td>2,500</td><td>50,000</td><td></td></tr>
<tr><td>Pennsylvania</td><td>750</td><td>50,000</td><td></td></tr>
<tr><td>Texas</td><td>2,500</td><td>None</td><td></td></tr>
<tr><td>Vermont</td><td>2,500</td><td>40,000</td><td>100,000</td><td></td></tr>
<tr><td>Washington</td><td>1,625</td><td>45,000</td><td>None</td><td>Credit</td><td>6.5% sales tax exempt, $1,625 cap</td></tr>
<tr><td>Average</td><td>2,363</td><td>50,583</td><td>125,000</td><td></td><td></td></tr>
</table>

California has an income cap of $150,000 for single tax filers, with increasing amounts for married couples filing jointly, and is also one of a few states that offers an extra incentive of $2,500 for low-income filers. The threshold for low-income is 400% of the poverty line. Colorado has varying amounts of benefit for vehicle class, income, and application time. Although difficult to discern, most state incentives are rebates, meaning they are a direct payment to the vehicle buyer, not a credit which could reduce an owed tax burden but does not refund any remaining amount if the burden is less than the maximum amount offered by the state. If the buyer does not owe any taxes after filing their returns, the credit would be $0, as in the case of the federal tax credit. Even the states labeled as “credit” are sales tax exemptions which immediately reduce the out of pocket expenses required as in Washington and Maryland, or have exceptions in place to add the remaining amount towards a tax refund, as in Colorado. Subsidies used throughout this study assume the “standard” income, meaning any additional amounts offered for low-income applicants are not considered.

The subsidies are complicated further when tracing the history of the incentive for each state, as the sensitivity analysis in section 4.1 takes into account vehicle model year and the comparison between the benefit and subsidy means that the subsidy may change year to year or not exist at all. All subsidy – benefit data shown in this study reflect these variations. For example, Massachusetts started its program in 2014 at $2,500 [58], meaning any vehicle model year before this had a state subsidy of $0. Massachusetts then reduced its subsidy to $1,500 in 2019 [59] and also instituted a $50,000 max price cap [60]. Then, the subsidy amount was increased back to $2,500 [60] but the max price cap remains [58].

3. Results

A baseline case using a non-luxury compact SUV to compare monetized climate, air quality, and combined impacts by state of ICEVs and BEVs separately is first shown in 3.1. Then, the climate, air quality, and combined monetized benefit of driving a BEV (BEV – ICEV) by state is shown in 3.2. Finally, a comparison of these benefits to the combined federal and state subsidies is shown in 3.3. Only the 48 continental US states are considered. The vehicle chosen for the baseline case results in the minimum BEV benefit or maximum BEV damage, compared to larger and/or luxury vehicles, as discussed in section 4.

3.1 Monetized climate and air quality damages of ICEVs and BEVs by state

The air quality damages from driving a 2022 Hyundai Kona 2.0L FWD, a base trim new ICEV compact SUV, for its full useful life of 173,151 miles are shown in Figure 1a. The damages are highest in states where driving occurs close to population centers, as $PM_{2.5}$ and O_3 concentrations are weighted by population in the concentration response functions (CRFs) used to produce the premature deaths/gram of emission state average scaling factors adapted from Dedoussi et al. [5]. This is exacerbated in states like New Jersey, a relatively small but densely populated state containing part of the largest metropolitan area in the US, resulting in higher scaling factors for road transport than other states (1.5×10^{-7} deaths/g direct $PM_{2.5}$ and 4.1×10^{-7} deaths/g NH_3). New York state has lower air quality damages than New Jersey partially due to lower scaling factors of 6×10^{-8} deaths/g direct $PM_{2.5}$ and 1.9×10^{-7} deaths/g NH_3, despite fully containing New York City. New York is a geographically much larger state with the upstate area less densely populated which leads to the lower scaling factor. Vehicle emission factors do not change across states in this study, and thus is not a contributing factor.

The three other pollutants, NO_x, SO_2, and VOCs, have scaling factors that are approximately 100 times smaller for road transport in New Jersey. First, this is because $PM_{2.5}$ causes approximately 90% of the early deaths caused in the road transport and electric generation sectors as a whole, compared to 10% for ozone according to Dedoussi et al. [5]. Second, in addition to direct $PM_{2.5}$, indirect (secondary) $PM_{2.5}$ is primarily formed from NO_x, SO_2, and NH_3, while O_3 is primarily formed from NO_x and VOCs [5]. Of the three precursor emissions to indirect $PM_{2.5}$, ammonia dominates in $PM_{2.5}$ formation by mass due to the chemical reactions which lead to $PM_{2.5}$. A simplified version [61] is shown below in Table 5, showing only representative pathways.

Table 5 – Simplified precursor reactions to form secondary $PM_{2.5}$

Precursor	Oxidation	$PM_{2.5}$ Formation	Precursor Molar Mass (g/mol)
NO_x	$NO_2 + OH \longrightarrow HNO_3$ (g)	NH_3 (g) + HNO_3 (g) $\leftrightarrow$ NH_4NO_3	46
SO_2	$SO_2 + 2OH \longrightarrow H_2SO_4$ (g)	$2NH_3$ (g) + H_2SO_4 $\leftrightarrow$ $(NH_4)_2SO_4$	64

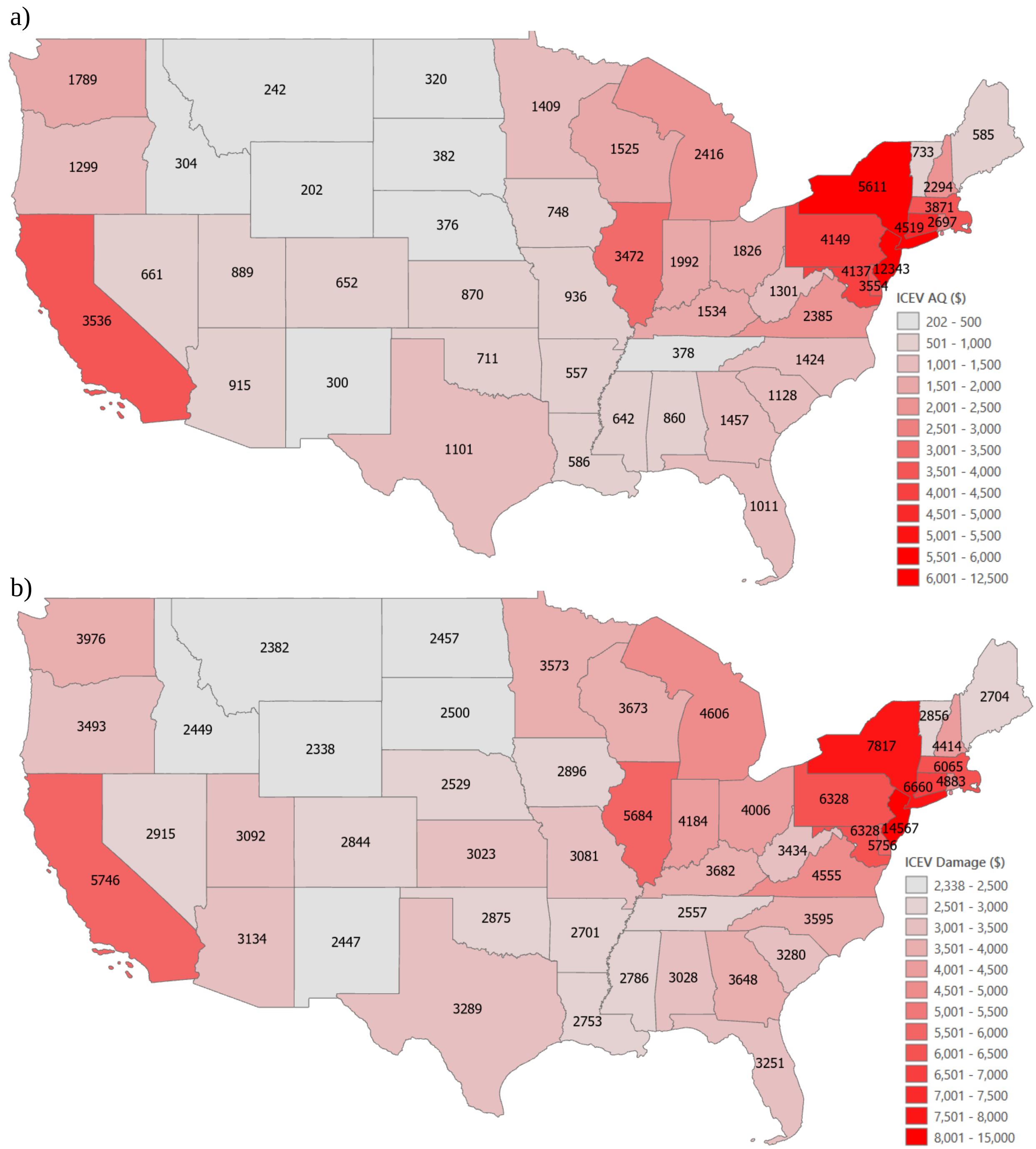


Figure 1 – Monetized damages of driving a 2022 Hyundai Kona 2.0L (Compact SUV ICEV Base Trim) for full useful life (173,151 miles) from (a) air quality (b) climate and air quality.

Nitrogen oxides are oxidized to form nitric acid, and reacts with ammonia to form ammonium nitrate particles, while sulfur dioxide is oxidized to form sulfuric acid, which reacts with ammonia to form ammonium sulfate particles. One mole of the precursor gases form 1 mole of $PM_{2.5}$, but given the same mass of the three precursor gases, ammonia would yield 2.7–3.7 times more $PM_{2.5}$ than NO_x and SO_2 due to the difference in molar mass. GEOS-Chem includes other factors like temperature and humidity [62], and models chemical reactions beyond this simplification [63] to produce the $PM_{2.5}$ and O_3 concentrations used to eventually estimate the mortality scaling factors employed in this study.

The climate damage for this vehicle (shown in Appendix) is not as geographically varied across the continental US ($2,117 to $2,254), compared to $242 (Montana) to $12,343 (New Jersey) for the air quality impact shown in Figure 1a. The only factor which changes the climate damage across states is the different proportion of urban, suburban, rural driving and local and highway roads within each region which make up the 11,104 miles driven annually, based upon VMT. Since this study assumes only urban local roads are assigned to the EPA city driving cycle, suburban local roads are assigned to the combined cycle, and all highway roads are assigned to the EPA highway cycle, the efficiency difference of 15% between city and highway cycles for the 2022 Hyundai Kona (30 and 35MPG, respectively) only manifests as a 6% variation in the climate damages across the US. For example, in New Jersey, 2,560 miles (23%) of the 11,104 miles driven annually are on urban local roads, while in Idaho, 1,184 miles (11%) are on urban local roads. This additional 1,300 miles of urban local driving in New Jersey partially contributes to $79 more climate damage. The sum of damages from climate and air quality is shown in Figure 1b.

The climate damages of driving a BEV shown in Figure 2a has a range of $2,259 compared to $137 for an ICEV because although vehicle emission factors also do not change for BEVs in this study, the grid CO_2 emission factors change across states from 3g/kWh in Vermont to 930g/kWh in Wyoming. Since the emission factors are different by state, and not by eGRID subregion or NERC region, these results assume the average electricity consumed in a state is exclusively produced by the same state. An alternative assumption is tested in the discussion. This partially contributed to the $7 climate damage for Vermont with 3gCO_2/kWh, as 81% of the state’s electric generation comes from hydro, solar, and wind [39]. This is in comparison to Wyoming where 84% of electricity is sourced from coal [39], which in turn is 60–80% carbon [64], contributing to higher CO_2 emissions upon combustion.

The air quality damages of driving a BEV shown in Figure 2b are impacted by both grid emission factors and mortality scaling factors. Wisconsin’s emission factors are 53mg $PM_{2.5}$/kWh and 7mg NH_3/kWh, and the mortality scaling factors are 1.1×10^{-8} deaths/g $PM_{2.5}$ and 2.2×10^{-8} NH_3 for power generation. Washington’s emission factors are 1mg/kWh for both pollutants, and the mortality scaling factors are 37% and 8% lower, respectively. Washington’s grid is 77% from zero emission sources, including hydro (62%), nuclear, solar, and wind (remaining 14%) [39]. This is in comparison to Wisconsin where 74% of electricity is sourced from fossil fuels [39], 42% of which is coal. The damage from both climate and air quality are shown in Figure 3.

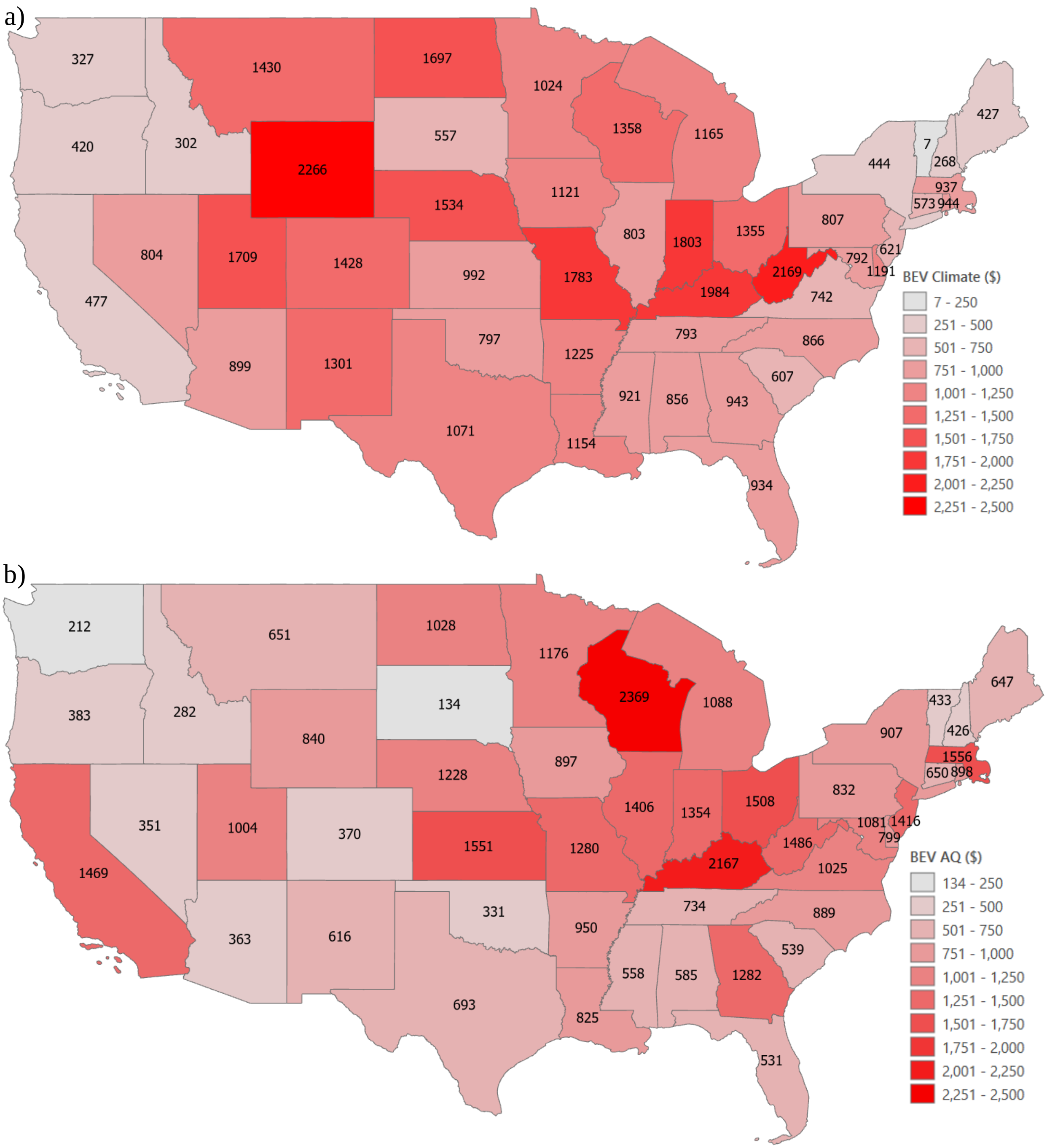


Figure 2 – Monetized damages of driving a 2021 Hyundai Kona EV (Compact SUV BEV Base Trim) for full useful life (173,151) miles from (a) climate (b) air quality.

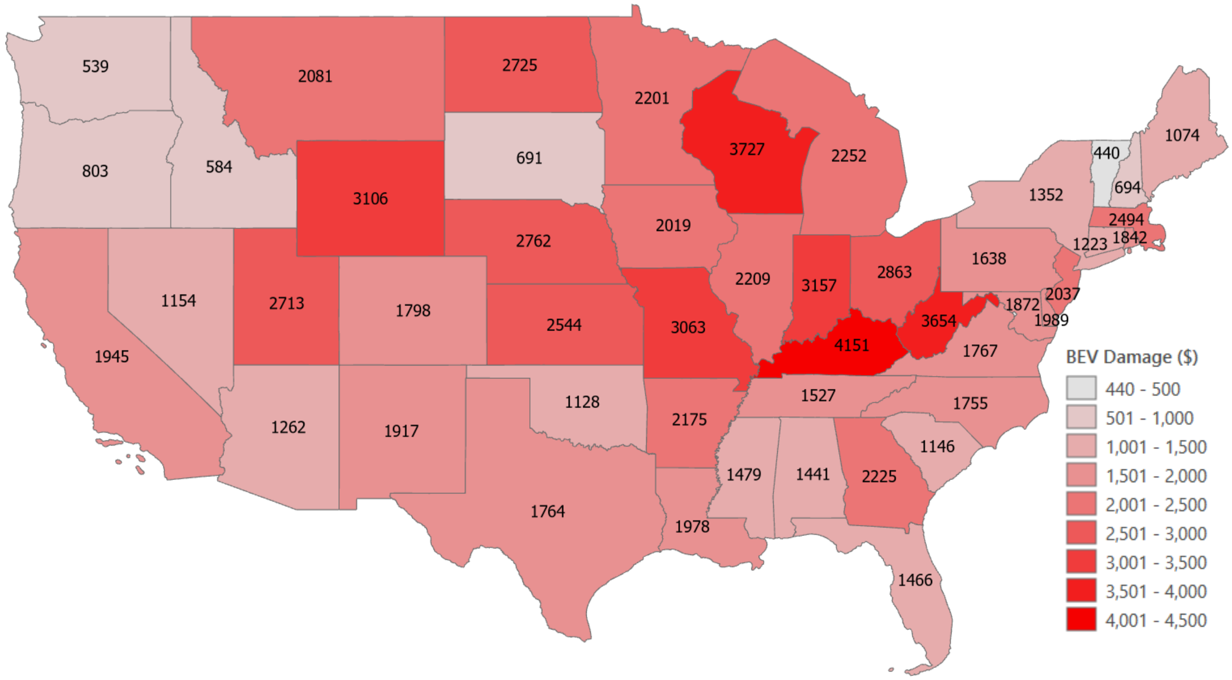


Figure 3 – Monetized climate and air quality damages of driving a 2022 Hyundai Kona EV for full useful life (173,151 miles)

3.2 Monetized climate and air quality benefits of driving a BEV over an ICEV

The benefit of driving a BEV is defined as ICEV Damage – BEV Damage, thus negative values mean that a BEV causes more damage. Climate benefits in Figure 4a show that driving an electric vehicle is less damaging for climate in all but two states: West Virginia and Wyoming, where values are negative and BEVs are thus more damaging than ICEVs. The grid emission factor in the state with the smallest negative value of -$35, West Virginia, is 889gCO_2/kWh [39, 40]. Since the damage is close to zero, any grid emission factor higher than this value will incur climate damages, not benefits, from driving a 2021 Hyundai Kona EV compared to a 2022 Hyundai Kona 2.0L FWD. The benefit for the remaining states is the result of a combination of several factors.

First, even if it is assumed the electricity to charge the BEV comes from fossil fuel sources such as natural gas, the thermal efficiency of a combined cycle plant is 50–60% [65, 66], while that of a mobile internal combustion engine is 20–38% [67]. Second, BEVs have virtually zero drivetrain energy losses due to the lack of a multi-speed transmission compared to 5–6% of total fuel energy in an ICEV, no idling losses (vs. 3%), and have regenerative braking to recoup energy otherwise dissipated as heat (vs. 4–7%) [68, 69]. The 2022 Hyundai Kona 2.0L FWD does not have an auto stop-start feature to reduce idling losses, which is included in EPA MPG ratings for vehicles with the feature. Even in vehicles with auto stop-start, idling losses are not completely eliminated because the feature is disabled after several consecutive stops and starts in quick succession. In total, 16–25% of fuel energy from gasoline is attributed to forward motion, compared to 86–90% of AC wall power consumption in a BEV [68, 69]. This study is not a life cycle analysis and thus does not explicitly include losses from electric transmission and emissions from fuel production and transportation for use in electric generation. However, the EPA MPGe ratings for BEVs used in this study include charging losses from AC wall power to

DC current fed into the battery (–10%), so on a tank-to-wheel basis, 46 states in the US offer a climate benefit with the 2021 Hyundai Kona EV.

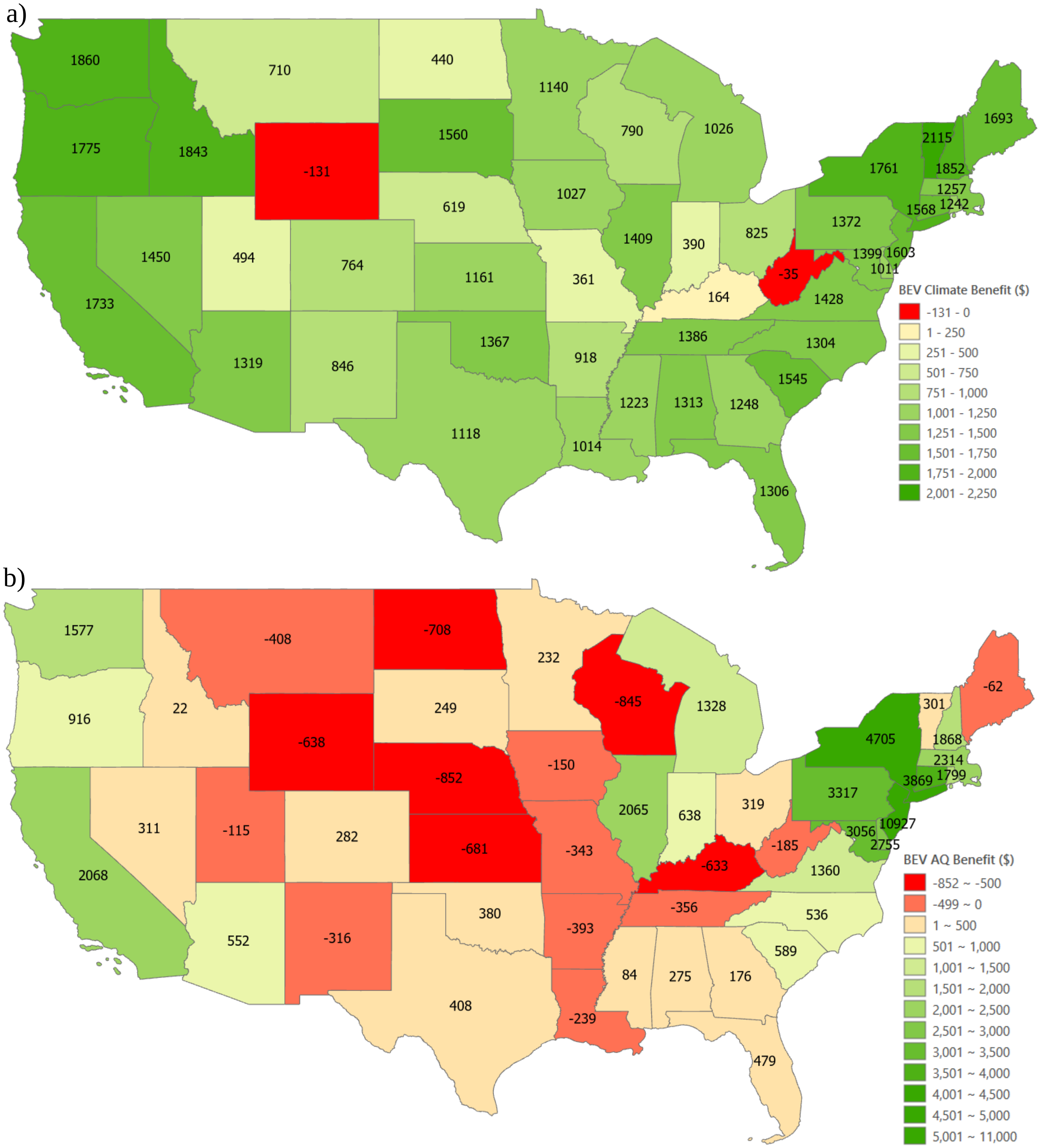


Figure 4 – Monetized benefit (ICEV – BEV) of driving a 2021 Hyundai Kona EV over a 2022 Hyundai Kona 2.0L FWD for full useful life (173,151 miles) from (a) climate (b) air quality.

The BEV benefit for air quality is positive in 32 states as shown in Figure 4b, and this is due to two factors. First, the state average grid emission factors and BEV vehicle efficiencies result in lower g/mi factors for BEVs. For example, the 2021 Hyundai Kona EV emits 2mg/mi of $PM_{2.5}$ and 0.4mg/mi of NH_3 in Washington on the estimated combined cycle, while the Hyundai

Kona 2.0L FWD emits 11mg/mi of $PM_{2.5}$ and 14mg/mi of NH_3 nationally. Second, the mortality scaling factors are lower for emissions from the electric grid because large power plants generally are not centrally located in urban areas, and thus are further away from population centers such that the mean weighted exposure would be lower. Figure 4b shows that the states containing the largest metropolitan areas by population in the US (New York, Los Angeles, Chicago, Washington DC) all have some of the largest air quality benefits in the country, from $1,799 to $10,927. Roads do not share this limitation and hence road transport emissions have higher mortality scaling factors even on a state average basis. In Washington for example, mortality scaling factors are 2.6×10^{-8} deaths/g $PM_{2.5}$, 5.6×10^{-8} deaths/g NH_3 for road transport, compared to 7×10^{-9} deaths/g $PM_{2.5}$ and 2×10^{-8} deaths/g NH_3 for electric generation.

For the remaining 16 states which have air quality damages due to BEVs compared to ICEVs, the grid emission factors are higher such that g/mi factors for BEVs are higher than that of ICEVs. Also, the advantage of lower mortality scaling factors for electric generation is eroded away in states with higher proportions of rural areas and smaller urban areas, such as Nebraska. The factors are 19% and 34% higher for SO_2 and NH_3, respectively, for the electric grid in Nebraska compared to road transport. This is in contrast to New Jersey where the same factors are 35% and 1% lower than those for road transport. In Nebraska, the effect of 206 times greater SO_2 emissions per year from driving the BEV becomes the dominant factor which contributes to over triple the number of deaths/year from all five pollutants when compared to the ICEV as shown in Table 6.

Table 6 – Nebraska deaths/g mortality scaling factors, emissions/yr from and deaths/yr caused by 2022 Hyundai Kona EV or 2.0L FWD, and ratio of BEV to ICEV deaths/yr

	NO_x	**$PM_{2.5}$**	**SO_2**	**NH_3**	**VOC**	**Sum**
Road Deaths/g	1.9×10^{-9}	6.9×10^{-9}	10^{-9}	6.1×10^{-9}	9.6×10^{-10}	
ICEV emissions g/yr	300	90	18	168	477	
ICEV deaths/yr	5.6×10^{-7}	6.21×10^{-7}	1.8×10^{-8}	10^{-6}	4.6×10^{-7}	2.7×10^{-6}
Electric deaths/g	1.8×10^{-9}	4.8×10^{-9}	1.2×10^{-9}	8.1×10^{-9}	7.8×10^{-10}	
BEV emissions g/yr	1,765	179	3,710	22.5	49	
BEV deaths/yr	3.2×10^{-6}	8.6×10^{-7}	4.4×10^{-6}	1.8×10^{-7}	3.8×10^{-8}	8.7×10^{-6}
BEV/ICEV deaths/yr	5.8	1.4	245	0.18	0.08	3.3

The electric grid in Nebraska is 55% sourced from coal [39], which has a typical sulfur content of 0.5–5%, producing SO_2 upon combustion [70]. Gasoline motor fuel nationally has a maximum sulfur content of 10ppm (0.001%) controlled by the EPA Tier 3 fuel standard [31], which is 2,750 times less than the average amount in coal by mass.

The combined climate and air quality benefit of BEVs is shown below in Figure 5. In all but 6 states, driving a 2021 Hyundai Kona EV is less damaging than a 2022 Hyundai Kona 2.0L FWD. In states such as Louisiana, the -$239 benefit ($239 damage) for air quality is smaller than the $1,014 benefit for climate and is a net $775 benefit. This is partly due to Louisiana's grid which is 70% natural gas, 7% coal, and 14% nuclear [39], which benefits BEV climate impact from the thermal efficiency advantages of a combined cycle plant over a mobile internal combustion engine (and zero impact for nuclear). This is in contrast to Wyoming which has damages from both climate and air quality, where 84% of electricity is from coal [39], and neither climate nor air quality benefits are observed compared to an ICE. This can result in higher SO_2 emissions in Wyoming due to higher coal use. The EPA limits pipeline natural gas sulfur content to maximum 8.5 ppm (0.0017%) [85], whereas coal has 0.5–5% on average [70].

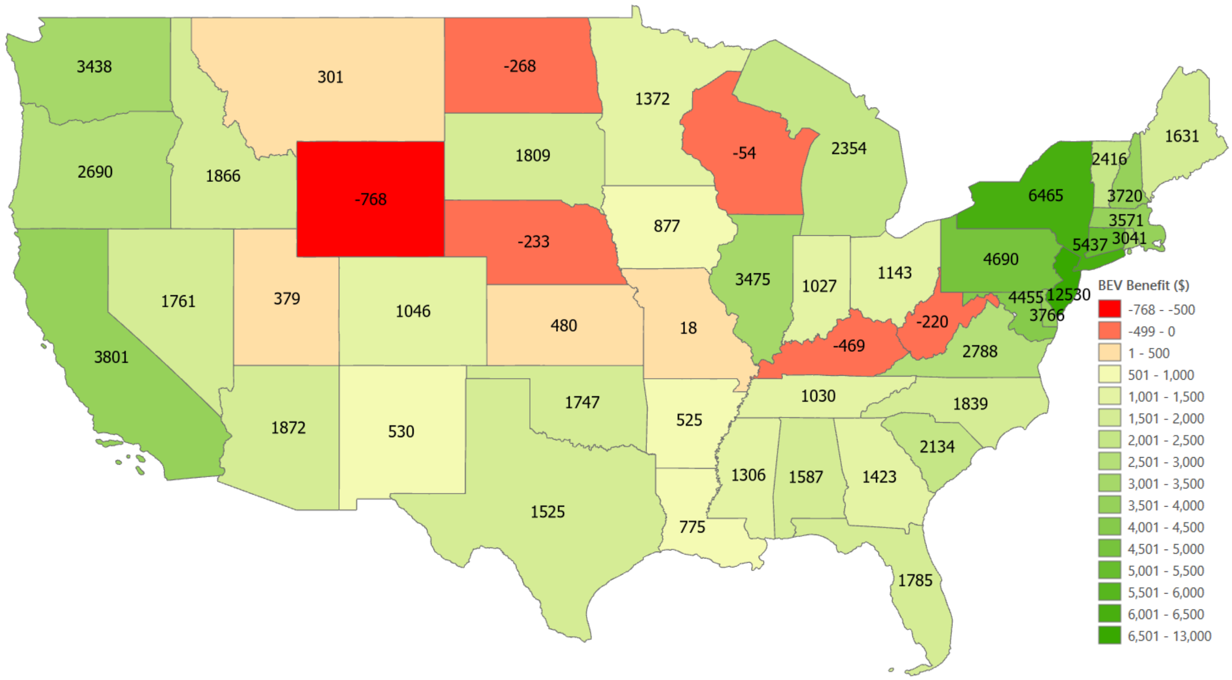
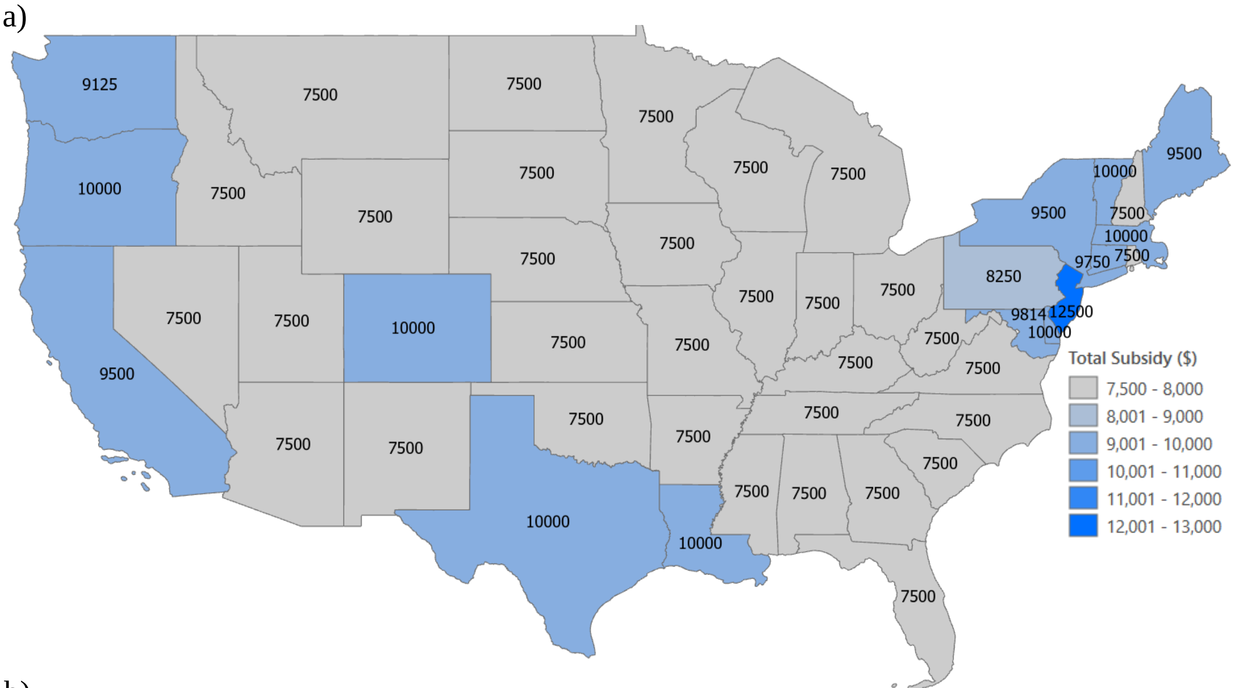


Figure 5 – Climate and air quality benefit of driving a 2021 Hyundai Kona EV over a 2022 Hyundai Kona 2.0L FWD for full useful life (173,151 miles)

3.3 Comparison of BEV benefits to subsidies by state

The subsidies by state in 2021 are visualized in Figure 6a. The $7,500 federal subsidy applies to every state, and varying state subsidies are added. Figure 6b shows the BEV benefit subtracted from the subsidy, such that the higher the value, the larger the misalignment between the subsidy and benefit. Larger misalignment values can mean that the benefit is not as large as the subsidy, as in New York where the subsidy is $9,500 and the benefit is $6,465, leading to a misalignment of $3,035. It can also represent a net damage from driving a BEV compared to the subsidy, as in the case of Wyoming with a $7,500 federal subsidy – [-$768 benefit] is equal to a $8,268 misalignment. Any misalignment smaller than $5,000 is from the eastern seaboard states, Virginia, and Illinois.

a)



b)

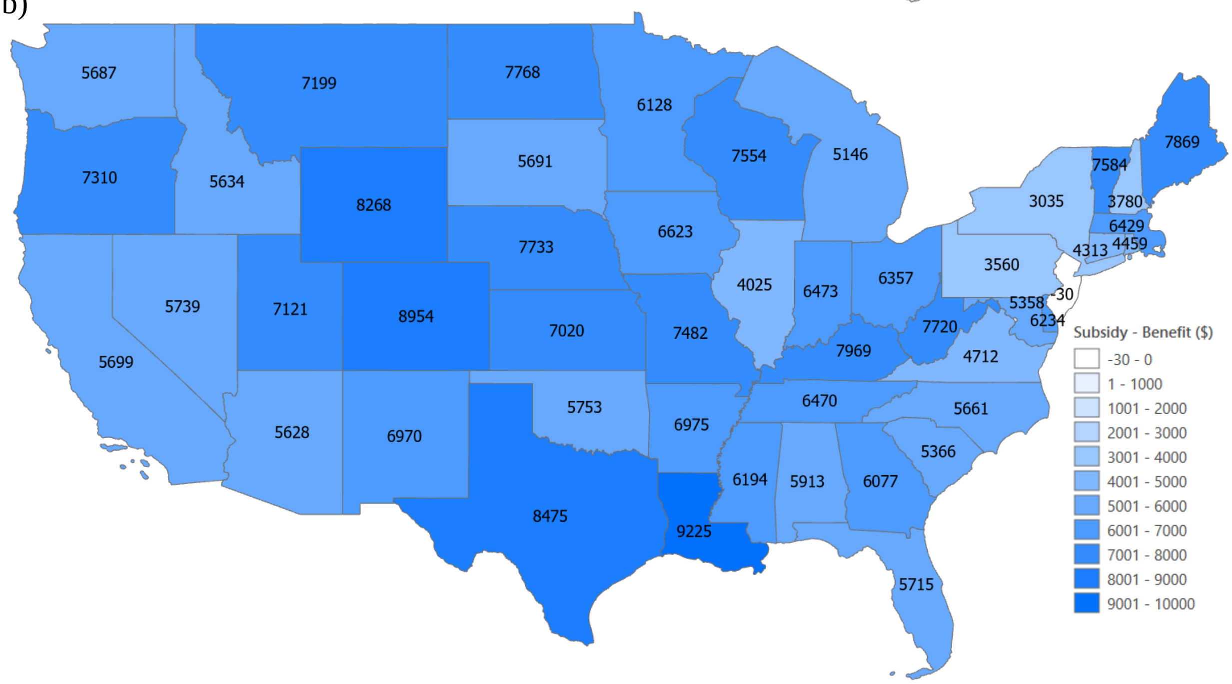


Figure 6 – Map of (a) federal and state EV subsidies. (b) comparison of federal and state subsidies to BEV benefits (subsidy – benefit).

To better visually differentiate these two cases, Figure 7 shows a scatterplot where moving towards the top right means a larger subsidy and benefit, and the bottom left means a smaller or zero state subsidy and smaller benefit. The minimum subsidy is $7,500, as the federal credit applies to all states. New York, Connecticut, Pennsylvania, Maryland, Delaware, New Jersey, and California are states which show benefits larger than those in any state with zero state subsidy; New Hampshire has the largest benefit out of the zero state subsidy states in the bottom left of the chart, at $3,720. Texas ($1,525), Colorado ($1,046), Louisiana ($775), and Maine ($1,630) offer subsidies but have similar or smaller BEV net benefits to the large cluster of states without state subsidies, including Florida ($1,785) and Idaho ($1,866). Every state which offers a state subsidy has a positive BEV net benefit. In turn, the states that do not offer a subsidy are also the group of points to the bottom left of the plot with smaller and even negative BEV net benefits (damages). 11 states, ranging from Wyoming (-$768) to New Mexico ($530) have smaller benefits or damages compared to the minimum benefit ($775) among the states with a state subsidy (Louisiana). In addition, the gap in BEV benefit between these two groups at the same misalignment levels is approximately $1,666 to $2,475. For example, Ohio and Massachusetts have subsidy – benefit differences of $6,357 and $6,429, respectively, but the BEV benefits are $1,143 and $3,571, respectively. The difference in BEV benefit, $2,428.11, is similar to the $2,500 state subsidy offered by Massachusetts, and the average state subsidy of $2,363. New Jersey is an outlier point as the only state where the subsidy nearly matches the benefit, with a net benefit of $12,530 ($1,603 climate + $10,926 air quality) and a total subsidy of $12,500 ($7,500 federal + $5,000 state).

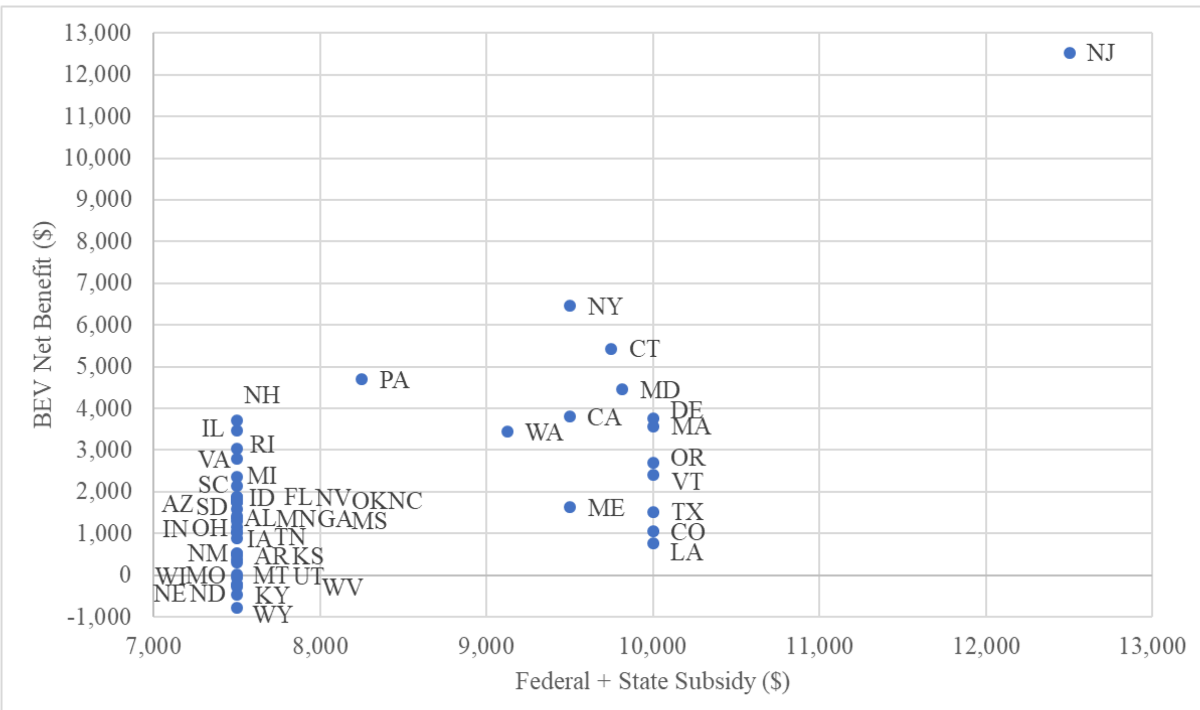


Figure 7 – Scatterplot of benefit of driving a BEV over an ICEV vs. federal and state subsidy

4. Discussion

Some of the key inputs to the baseline case, including the vehicle and the electric grid, are changed to see the sensitivity of benefits to these variables. Since the baseline case used the non-luxury compact SUV to show the minimum BEV benefit, the benefits by state are calculated using the large luxury sedan for the sensitivity analysis to show the maximum BEV benefit, establishing a range. Using Massachusetts as an example, I then show the monetized climate and air quality impacts, BEV benefits, and comparison to subsidy for every BEV vehicle class available today compared to their respective gasoline ICEV counterparts. I also use the NERC marginal grid emission factors instead of state grid average values and report the change in impacts for BEVs. I also analyze the contribution of each considered pollutant, regions and road types to the monetized impacts, and the importance of exported air quality impacts.

4.1 Sensitivity of benefits to vehicle size, type, trim level, and model year

The vehicle is changed from a 2021 Hyundai Kona EV (BEV) and 2022 Hyundai Kona 2.0L FWD (ICEV) to a 2021 Tesla Model S Performance (BEV) and a 2020 Mercedes-Benz S65 AMG, switching from a base trim non-luxury compact SUV to a top trim large luxury sedan. Climate, air quality, and net damages for both ICEV and BEV are shown in the Appendix. Figure 8a shows the climate benefits become positive for all states, whereas it is negative in 4 states with the base compact SUV. The BEV climate impact increases range from $0.30 (Vermont) to $109 (Utah) due to increased total energy use/year, partly from the increase in power, range, curb weight, and battery capacity (64 to 100kWh). The ICEV climate impact increases range from $1,576 (New Hampshire) to $2,261 (Nevada), thus dominating the net BEV climate benefit increases of $1,567 (New Hampshire) to $2,169 (Nevada). The significantly larger increase in ICEV climate impact compared to the BEV comes from vehicle attribute changes shown below in Table 7 [71, 72, 73].

Table 7 – Vehicle characteristics and annual energy use in Massachusetts

	Energy (kWh/yr)	Power (hp)	Range (mi)	Wt. (lb)
2021 Hyundai Kona EV	3,217	201	248	3,715
2021 Tesla Model S Performance	3,415	778	348	4,941
% Change (BEV)	6	287	35	33
2022 Hyundai Kona 2.0L FWD	11,213	147	422	2,899
2020 Mercedes-Benz S65 AMG	20,872	621	394	4,969
% Change (ICEV)	86	322	-7	71

There is a 198kWh/year increase in energy consumption for a 577hp increase in power for the BEV, while there are 9,659kWh/year and 474hp increases, respectively, for the ICEV. The marginal power increase is 2.9hp/annual kWh for the Tesla Model S, 0.05 for the Mercedes S65, thus the BEV has a 60 times more advantageous tradeoff in energy consumption per unit of performance increase (energy is wall power for BEV, fuel energy for ICEV). The 6.5L V12 bi-turbo engine in the Mercedes consumes more fuel per unit of power gained than the two electric motors, inverter, and larger battery in the Tesla, as ICEs have typical thermal efficiencies of 20–38%, while electric motors are 85–90% efficient in electrical to rotational energy conversion. Since CO_2 is directly proportional to fuel (energy) consumption, the 1.9 times higher fuel consumption in the Mercedes compared to the Hyundai also results in approximately double the monetized climate impact (for example, $2,194 to $4,168 in Massachusetts).

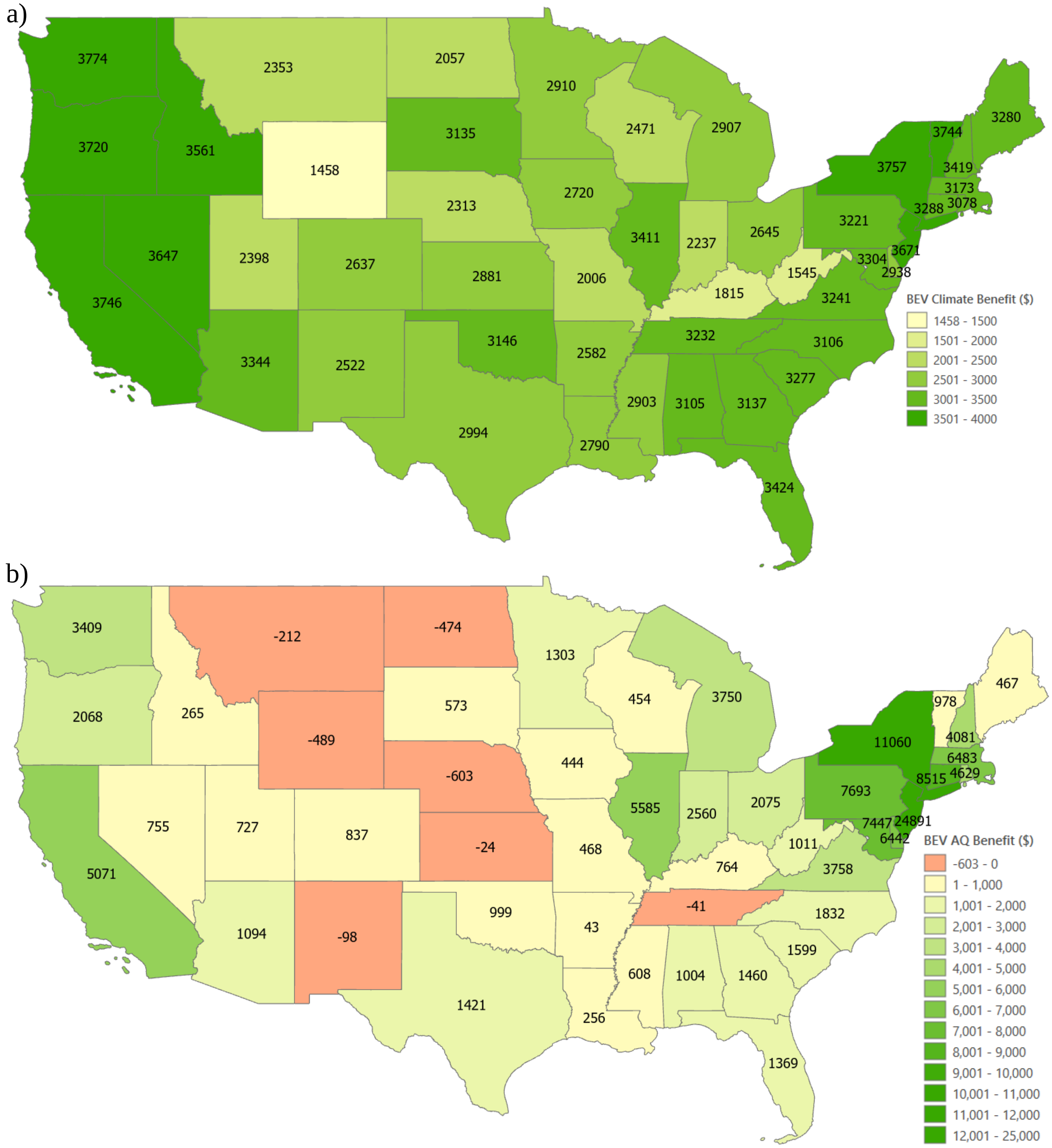


Figure 8 - Monetized benefits of driving a 2021 Tesla Model S Performance (Large Luxury Sedan BEV Top Trim) over a 2020 Mercedes-Benz S65 AMG (ICEV Top Trim) for full useful life (173,151 miles) from (a) climate (b) air quality

When comparing the base to top trim of the same large luxury sedan class, the Tesla Model S shows a 139% increase in power for 0% change in efficiency, while the Mercedes S-

Class shows a 72% increase in power for a 37.5% increase in energy consumption, as shown in Figure 9.

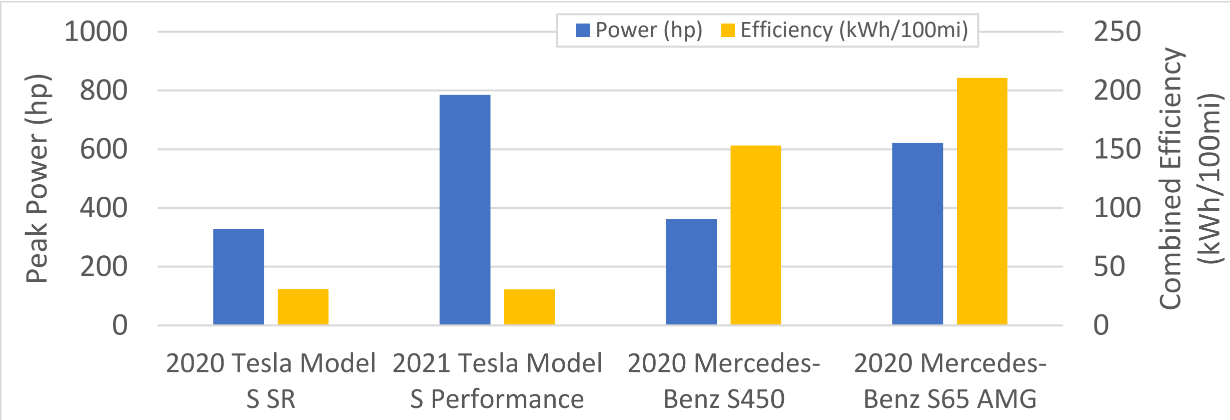


Figure 9 – Peak power and combined cycle "efficiency" for large luxury sedan class by trim

Figure 8b shows the air quality benefit is now positive in 41 states instead of 32, and this is due to the EPA smog rating of the Mercedes, which is in Federal Tier 3 Bin 125 (125mg/mi NO_x+NMOG), while the Hyundai is in Bin 70 (70mg/mi NO_x+NMOG) [44]. The $PM_{2.5}$ factor in Tier 3 does not change for any bin, at an average 4.5mg/mi (except Bin 0 = 0g/mi for BEV) [31]. The $PM_{2.5}$ for brakewear is 10% higher for the Hyundai as it is classed as an SUV compared to a car for the Mercedes. The final emission factors were calculated based on methods described in section 2.3, and the combined values (suburban local road driving) are shown below in Table 8.

Table 8 – Combined cycle estimated pollutant emission factors for 2021 Hyundai Kona 2.0L FWD and 2020 Mercedes-Benz S65 AMG

Emission factors in mg/mi	NO_x	$PM_{2.5}$	SO_2	NH_3	VOC
2021 Hyundai Kona 2.0L	25	10.8	2	14	45
2020 Mercedes-Benz S65	54	11.3	4	37	71
% Change	118	4.2	104	156	57

Since SO_2 scales with fuel consumption, NH_3, VOC are assumed to scale with fuel consumption, and NO_x is varied across urban/suburban/rural regions by fuel consumption, the AQ monetized impact also approximately doubles in every state for the Mercedes. The BEV air quality impact increases –5%, and thus the BEV benefit is dominated by the ICEV AQ impact doubling from switching to the large luxury sedan class. The minimum ICEV air quality impact increase is in Wyoming ($202 to $386), and the maximum increase is in New Jersey ($12,343 to $26,405), resulting in a net BEV AQ benefit increase of $149 in Wyoming and $13,964 in New Jersey.

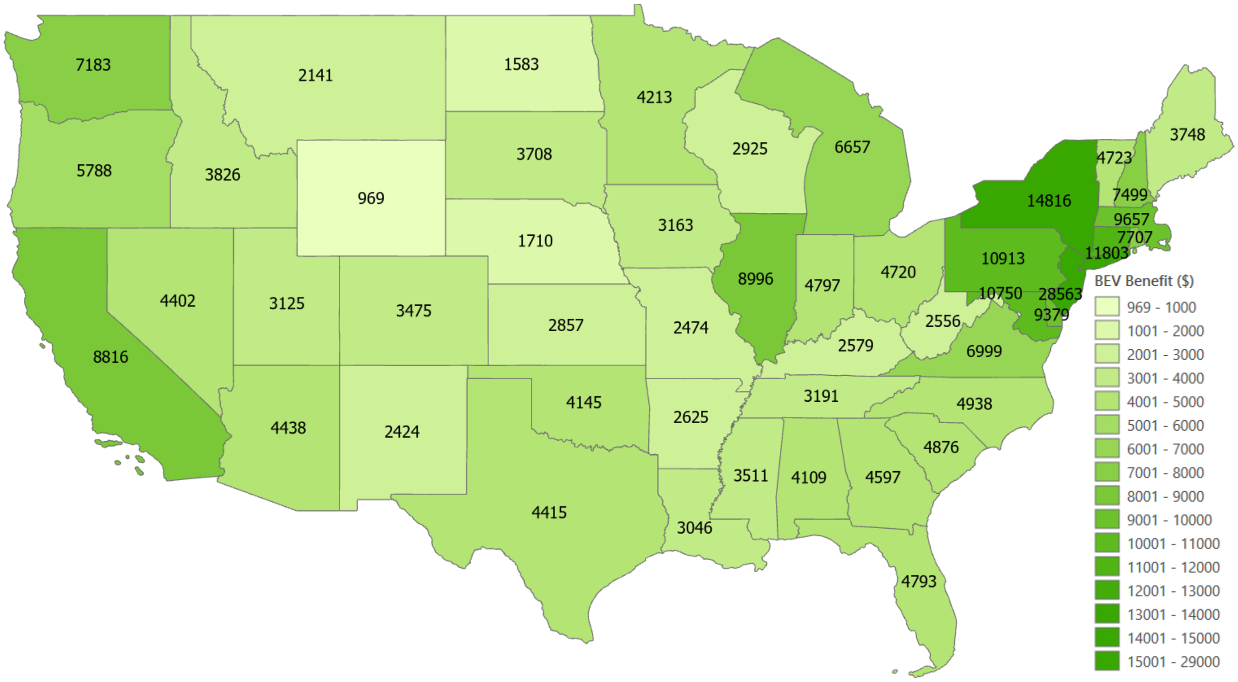


Figure 10 – Monetized climate and air quality benefit of driving a 2021 Tesla Model S Performance over a 2020 Mercedes-Benz S65 AMG for full useful life (173,151 miles)

The combined climate and air quality benefit shown in the large luxury sedan class in Figure 10 is positive in all 48 states compared to 42 (base case), primarily due to ICEV climate and AQ impacts both doubling for the Mercedes over the Hyundai. The climate benefit dominates the combined impact in less populated areas of the Midwest where the AQ impact is smaller for the road transportation sector and the grid pollutant emissions factors and mortality scaling factors are higher, such as Arkansas with a $2,582 climate benefit and $43 air quality benefit, totaling $2,625. No subsidy comparison map is shown for the large luxury sedan because it does not qualify for the $7,500 federal tax credit due to the 200,000 vehicle expiration for Tesla, nor most state credits due to maximum MSRP caps (average $50,000 cap vs. $91,990 Tesla MSRP).

Figure 11a shows a comparison of monetized climate and air quality damages of BEVs and ICEVs across different vehicle types and sizes, model years, and trim levels in Massachusetts. The vehicle types encompass every BEV segment available in the market at the time of writing. The model years cover the first year the BEV was available until 2021 for each segment. The bar values are for the base trim, and the whiskers show the top trim total climate and air quality damage. Thus, for each attribute, the range of possible damages are calculated. First, the compact SUV and large luxury sedan classes represent the minimum and maximum difference in combined damages, respectively. The compact SUV was chosen for the results section to show the worst case scenario for the BEV with the smallest BEV benefit, and Figures 8 and 10 show the best case scenario with the largest BEV benefits. Second, for luxury vehicles, there is a 30% average increase in total damage for moving up from a compact to a large ICEV for the base trim, compared to 23% for the size upgrade in BEVs. This increase is halved when looking across the top trims, with an average 15% increase for ICEVs and 10% increase for BEVs.

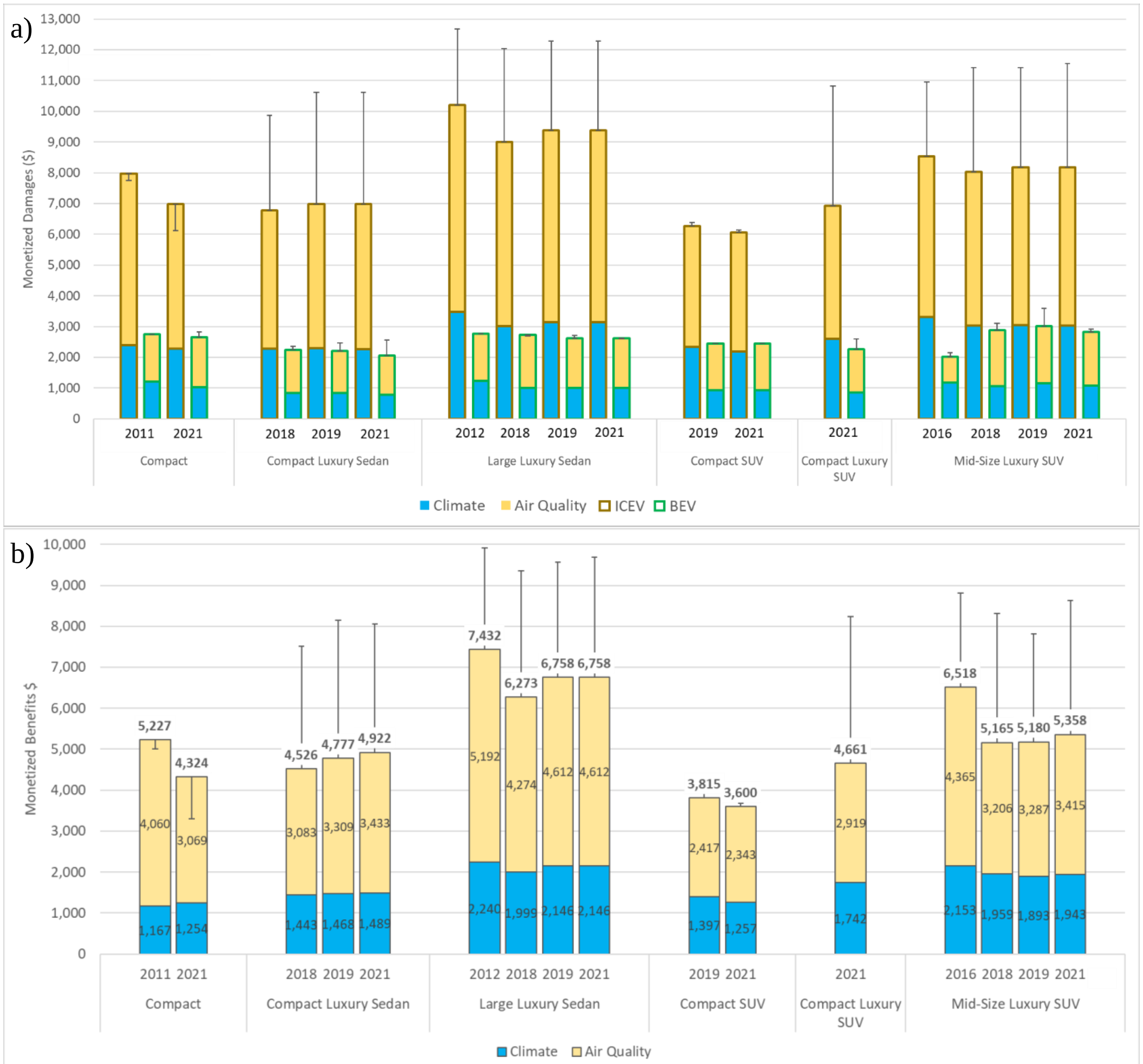


Figure 11 – (a) Monetized climate and air quality impacts and (b) Benefits in Massachusetts by vehicle size, type, model year, trim (bar: base, whisker: top).

The gap is smaller than when the minimum and maximum cases of the Hyundai Kona and Tesla Model S Performance/Mercedes S65 were shown in the results, partly because the compact luxury sedan ICEV has a 3.0L I6 turbo (BMW 3 Series) for the top trim, while the Mercedes S65 has a 6.5L V12 bi-turbo. In the non-luxury space, the trend is reversed, with the compact SUV (Hyundai Kona) resulting in less damage for the ICEV than the compact (Nissan Versa). Although the Nissan is in Tier 3 Bin 30 compared to Bin 70 for the Hyundai, the city fuel consumption is 11% lower for the Nissan [44] and since ammonia is taken to scale with CO_2 (and thus fuel economy), the dominant NH_3 damages are 32% larger for the Nissan when combined with the mortality scaling factor for road transport in Massachusetts.

Figure 11a also shows that across all luxury segments, the top trim damages for ICEVs are 40% higher than the base trim, and 7% higher for BEVs, despite similar or higher power output in BEVs. This trend is again reversed for the non-luxury segment, where the top trim actually reduces the damage from ICEVs for the compact and has a 1% increase for the compact SUV. The base trim Nissan Versa has a 5-speed manual gearbox, while the top trim comes with a continuous variable transmission (CVT), and this decreases the combined fuel consumption by 14% [44]. The Nissan Versa is one of the most affordable vehicles on the market with a base price of $15,930 including destination [74], less than half of the price of an average new car sold in the US at $38,723 [75]. Fuel saving technologies are expensive to implement for the manufacturer and thus some are missing on the cheapest models. At the same time, cost conscious consumers targeted by the compact budget vehicles are willing to pay a premium to move up to the higher trim if it offers fuel cost savings which will overcome the initial additional investment. This is in contrast to luxury vehicles, where the consumer is less sensitive to fuel costs and instead expects more power as one of the advantages when paying a premium.

Figure 11a shows that over the past 2 to 10 years, all ICEVs at the base trim level have reduced their damages by an average of 7% total except for the compact luxury sedan (BMW 3 Series). The gasoline vehicle industry, with over 100 years of experience in advancing ICE technology, is still showing efficiency increases in the face of increasingly stringent government CAFE (Corporate Average Fuel Economy) and EPA Tier 3 standards. Ultimately, cars such as the Mercedes S65 with its 6.5L V12 bi-turbo are being replaced by the S63 with a 4.0 V8 bi-turbo, following the industry trend of increasingly downsizing and turbocharging engines to meet these standards. At the same time however, some argue that the ICEV industry has entered a “golden age of horsepower” [76] before gasoline vehicles are slowly reduced in sales over the next several decades, as models such as the Dodge Demon with 840hp make more power accessible to more people than ever before, and luxury vehicles tout power gains with each update every few years. Automakers are able to do so partly by earning credits from the sale of fuel efficient hybrid, plug-in hybrid, and BEVs which exceed the required CAFE, and also trading credits [77] with other automakers who have additional credits. BEVs have reduced their damages by an average of 6% total over the past decade with two exceptions. The compact SUV for which there has been no update to the Hyundai Kona EV from 2019 to 2021 did not change, and the mid-size luxury SUV (Tesla Model X) which eliminated its base model 60D (60kWh) variant after 2016 [78], showed a 38% damage increase as the base model is now the long range variant (100kWh). Tesla has repeated this practice on the Model 3 [79] and Model Y [80], advertising a low price base model and claiming to increase BEV market penetration, only making it available as a phone or in-store order instead of online, then removing it from the market soon after, citing low range concerns. The 6% BEV damage reduction is a combination of a 11% reduction in BEV energy consumption over the past decade while the industry is still in its infancy, and a 324% increase in NH_3 grid emissions as the Pilgrim nuclear plant in Plymouth, Mass. shut down in 2019 and was replaced by natural gas capacity due to low wholesale energy prices [81].

Figure 11b shows the benefit decreasing by an average of 12%, except the compact luxury sedan where the benefit is increasing by 9% from the oldest to newest vehicle for each segment. Despite the 6% increase in BEV efficiency, the 7% increase in ICEV efficiency as well as the increase in emissions grid factors in Massachusetts across some pollutants contributes to this decrease in benefit. It is not practical to show the analysis in this section for the other 47 states, but the damages are sensitive to both road and electric mortality scaling factors and the grid emission factors for BEVs, thus the results can change not only the benefits but the trends discussed thus far. For example, in Connecticut, the large luxury sedan and mid-size SUV shows BEV benefit increasing by 8% and 10% respectively from 2012 to 2021 for the top trim due to grid emission factor reductions of 92% in $PM_{2.5}$ emissions during the same period. Map plots of monetized climate, air quality, and combined damages for the 2020 Mercedes-Benz S65, 2021 Tesla Model S Performance, and bar charts of emission factors are available in the Appendix.

4.2 Comparison of benefits to subsidies by vehicle attribute and subsidy phase-out

Figure 12 shows the comparison of climate and air quality benefits of BEVs over ICEVs to subsidies (subsidy – benefit) by vehicle type and the subsidies by federal and state for Massachusetts. The 2021 Hyundai Kona (compact SUV) was chosen for section 3 not only because it is the limit case for smallest BEV climate and air quality benefit over an ICEV, but also because it is one of the only brand new vehicles in 2021 that qualifies for the full $7,500 federal tax credit as well as the full state incentive from those that offer one. Although Tesla as a manufacturer remains the most selling EV brand [82], its federal tax credit phased out completely starting January 2020 [24] and is not used as a useful comparison to produce the subsidy – benefit map in section 3.3. The subsidy is halved twice then eliminated completely after a manufacturer produces 200,000 units, at specific time intervals determined by the government which may be different for each company. For Tesla, it was $7,500 January 2010 to December 2018, then $3,750 January to June 2019, then $1,875 July to December 2019, then $0 thereafter. General Motors is the only other firm which has reached this limit [24]. The full incentive in Massachusetts is $2,500 [58], where the state subsidy program started in 2014, so vehicles like the 2011 Nissan Leaf and 2012 Tesla Model S did not qualify. The program reduced its subsidy to $1,500 in 2019 [59], and changed back to $2,500 in 2020. A max MSRP cap (including destination, excluding tax, title) of $50,000 was introduced in 2019 [60] and remains today. The misalignment (in dashed orange line above each bar of benefit) is the subsidy – benefit, with matched subsidy for each vehicle trim, size, and model year. Subsidies A, B, and C are for each possible combination of federal and state subsidy depending on the vehicle. The only other vehicle category that also receives the maximum $10,000 total subsidy in Massachusetts is the compact class Nissan Leaf.

Another nuance is that federal subsidies are credits, meaning they are calculated based upon an individual or jointly filed tax bill, and if the person or couple does not owe any taxes or is owed a refund from the US government, the federal EV subsidy is $0. The credit only subtracts a maximum of $7,500 from those who, based upon their tax return, owe tax to the government. If they do owe tax but it is less than $7,500, they do not receive the remaining amount separately as a refund [83]. There is, however, no maximum price cap for vehicle eligibility nor any maximum income limit, thus it applies to anyone (likely at least middle or high-income buyers) who has a positive tax bill purchasing a $38,565 Hyundai Kona EV or a $119,990 Tesla Model X Plaid. This is in contrast to tax incentives in the majority of states which are direct rebates to applicants with maximum income limits and price caps. This would more often apply to lower and middle income applicants who are more likely not to owe several thousands in taxes but would be receiving a check regardless of their tax bill and eligible instead by falling under the maximum income cap and maximum vehicle price cap. The amount would also not vary by tax bill, and everyone would receive the same stated amount, $2,500 in the case of Massachusetts. The exceptions are additional incentives for low-income applicants available in a few states such as California with a threshold which varies across states, and sales tax waivers of the MSRP (some with maximum rebate amount caps) which would vary by vehicle.

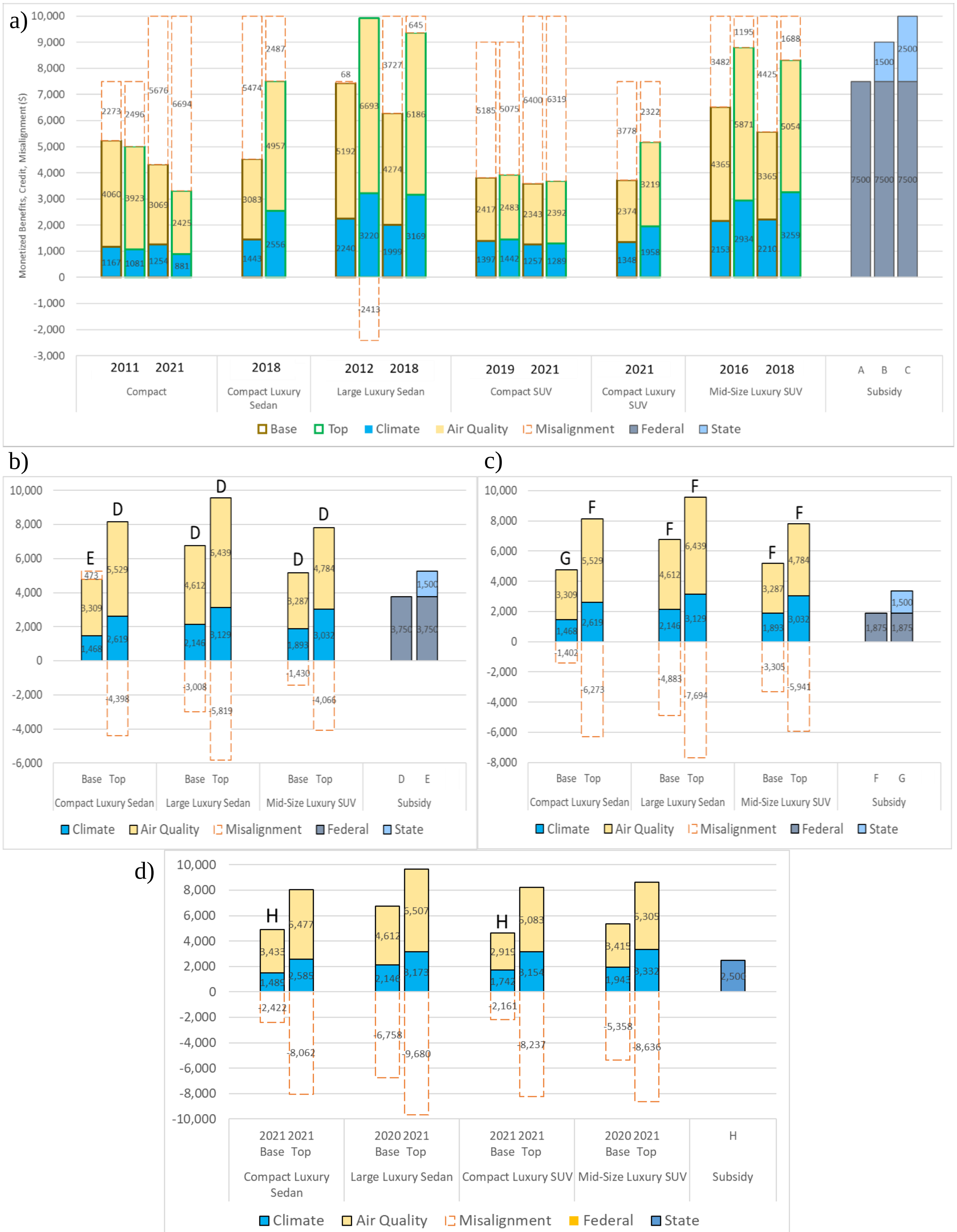


Figure 12 – (a) BEV benefit comparison to subsidy by vehicle size, trim, model year in MA for federal credit of (a) $7,500 (b) $3,750 (c) $1,875 (d) $0

In Figure 12a, the only vehicle which has a benefit that exceeds the combined federal and state subsidy in Massachusetts (negative misalignment value in orange dotted line below the benefit bar) is the 2012 Tesla Model S (large luxury sedan) top trim benefit over the 2012 Mercedes-Benz S65 AMG, with a -$2,413 misalignment. The base trim comes close to matching the subsidy at $68 misalignment. All other vehicles lie between this minimum misalignment and the maximum misalignment of the compact SUV top trim at $6,694. The subsidy – benefit comparisons shift for different states where they may be smaller or larger than those in Massachusetts. Figure 12b and c show the same set of vehicles purchased during either 1H or 2H 2019, which would receive either a $3,750 or $1,875 due to the Tesla federal subsidy phase-out. Tesla is the only vehicle available in the category or the sales leader in the EV space for the size class, and is thus chosen. For subsidies D, E, F, and G, they are labeled above the vehicle for which the subsidy applies for additional clarity as the negative misalignments make it less obvious to which subsidy the misalignment and benefit add up to. For the $3,750 federal credit, every vehicle except the 2019 Tesla Model 3 Standard Range has a benefit greater than the subsidy, and with the $1,875 credit, every vehicle has a negative misalignment. However, Figures 12b, c, and d seemingly show a smaller federal and state government investment producing the same or greater amount of climate and air quality benefit compared to the full federal and state subsidy case shown in Figure 12a, especially as luxury vehicles like Teslas have larger benefits than the compact and compact SUV class which would receive larger subsidies. Finally, Figure 12d shows new vehicles with fully expired ($0) federal subsidies, with only the 2021 Tesla Model 3 Standard Range Plus and Tesla Model Y Standard Range falling below the $50,000 MSRP cap for the Massachusetts subsidy and the remaining vehicles receiving neither federal nor state subsidies. This results in the maximum misalignment seen with any vehicle in Massachusetts thus far, with -$9,680 for the 2021 Tesla Model S Performance. Although determining the influence of tax credits on buyers' willingness to purchase BEVs is outside of the scope of this study, Tal and Nicholas [84] show that 30% of BEV purchase decisions can be attributed to the federal tax credit, with some models like the Nissan LEAF reaching 50%. Thus, at least in the short term, the decreasing subsidies may actually be seen as an effective "bonus" for achieving climate and air quality impact with little or even $0 government investment.

4.3 Sensitivity of benefits to marginal NERC region vs. average state grid emissions

The maps shown in results section 3 and discussion section 4.1 are using average grid emissions for each state, assuming that all power used to charge BEVs in the state is produced in the same state. In this section, a dispatch model which simulates CO_2, NO_x, and SO_2 emissions by hour of day and by summer, winter, and spring/fall, is used to calculate the annual emissions from charging a BEV for its full useful life [46]. $PM_{2.5}$, NH_3, and VOCs remain at the state average values as these were not available from the dispatch model. This assumes the states within a NERC region have equal emission factors as any state within could be transmitting power to another, and that all power comes only from fossil fuels, excluding renewables and nuclear sources. This is based on assuming that charging a BEV is a marginal addition to the baseload which is already using 100% of any available renewable capacity, thus any dispatched electricity is sourced from fossil fuels.

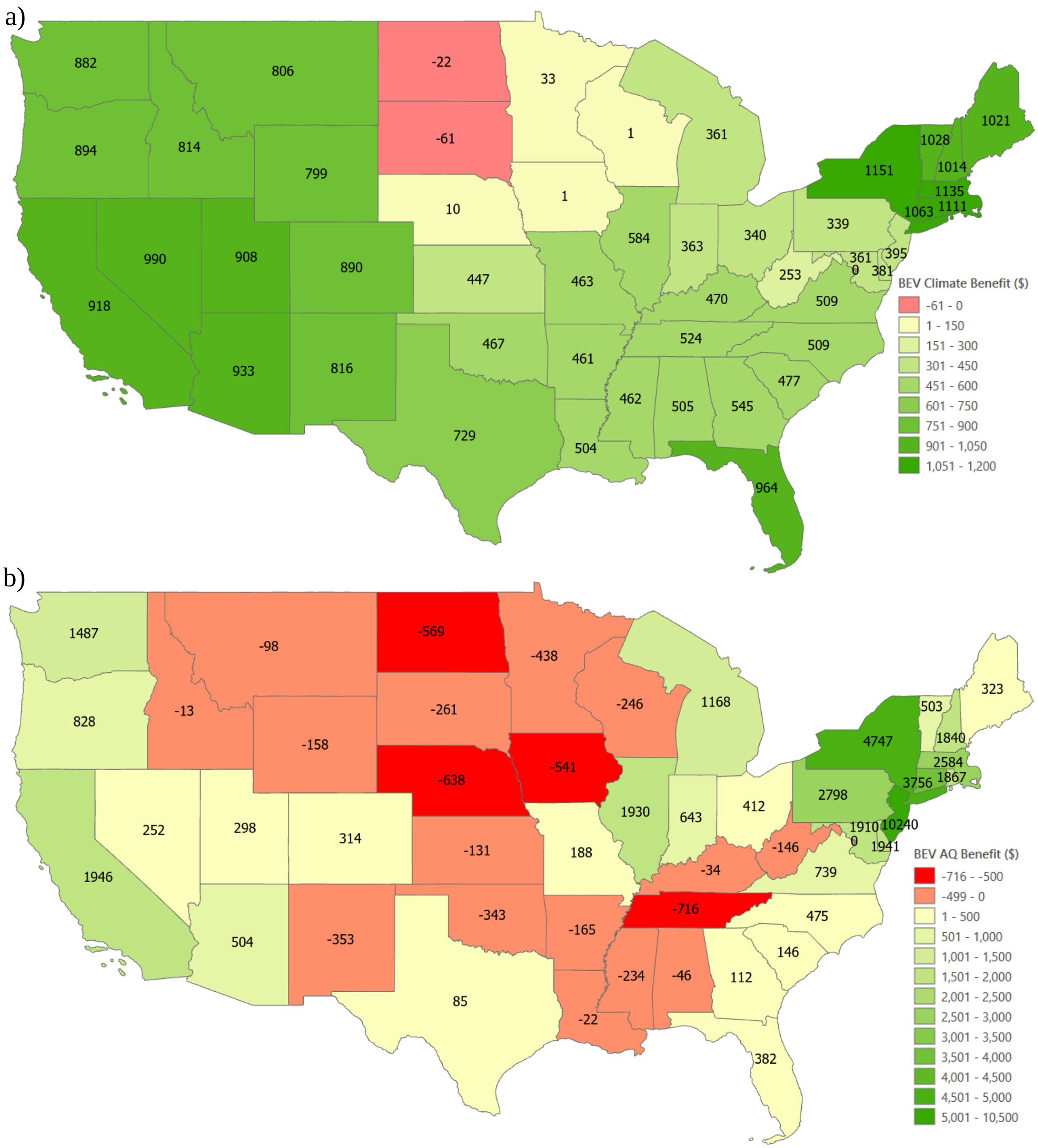


Figure 13 – (a) Monetized benefit of 2021 Hyundai Kona EV over 2021 Hyundai Kona 2.0L FWD with marginal NERC grid emissions for (a) climate (b) air quality

The BEV climate, air quality, and net damages are shown in the Appendix. The BEV climate benefit over an ICEV shown in Figure 13a is reduced by $725, or 56% on average in 38 states where the marginal NERC grid has higher emission factors than the state average. Two states of the 38, North and South Dakota, change from climate benefits to damages with the marginal grid driving a BEV over an ICEV (negative values/red on map). The climate benefit is increased by $395 or 161% in the remaining 10 states where the marginal grid emits less emissions than the state average grid, and 4 of these, Kansas, West Virginia, Wisconsin, and Wyoming, switch from having climate damages with the average grid to benefits with the marginal grid. In total, the number of states which have climate damages from BEVs is reduced from 4 to 2 with the marginal grid, and shows the marginal grid is not necessarily always higher in emissions than the state average if there are neighboring states which are lower in emissions and thus lower the NERC region average, even when considering only fossil fuel sources.

The BEV air quality benefit shown in Figure 13b decreases by $321, or 76% on average in 26 states. In 6 of the 26 states, Alabama, Idaho, Minnesota, Mississippi, Oklahoma, and South Dakota, the benefit turns into damage. The benefit increases in the remaining 20 states by $271, or 98% on average. In 3 states, Maine, Missouri, and Utah, the air quality damage turns positive into a benefit. Overall, 29 states have an air quality benefit compared to 32 with the average grid.

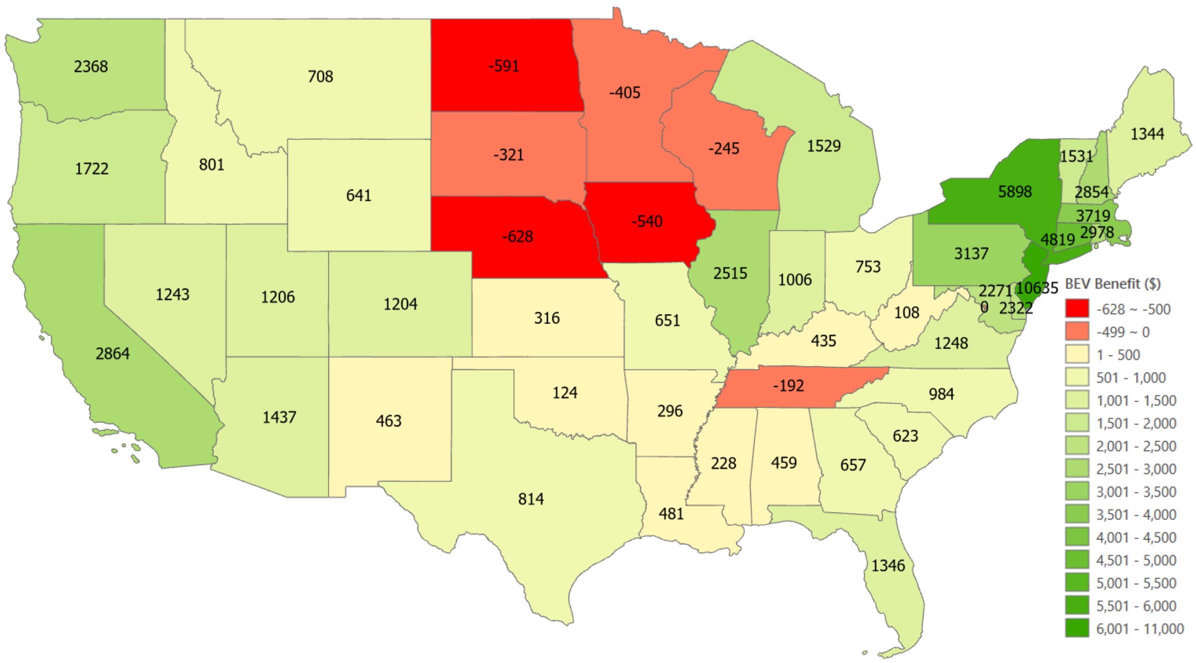


Figure 14 – Monetized climate and air quality of 2021 Hyundai Kona EV over 2021 Hyundai Kona 2.0L FWD with marginal NERC grid emissions from dispatch model

The net BEV benefit from climate and air quality diminishes by an average of $940, or 47% in 37 states, using marginal grid emissions. In 4 states, Iowa, Minnesota, South Dakota, and Tennessee, the benefit changes to damage. In the remaining 11 states, net BEV benefit increases by an average of $692, or 165%. In 5 states, Kansas, Kentucky, Missouri, West Virginia, and Wyoming, BEV damages convert into benefits. Figure 14 shows that there is a combined climate and air quality benefit in 41 states, compared to 40 states with the base case state average grid.

The subsidy-benefit comparison is shown in the Appendix. Even with the marginal grid, the highest benefit BEV eligible for each respective state that offers a state incentive does not match the subsidy. In states except Colorado, Texas, and Louisiana, the state incentive offered has a maximum MSRP cap of $40,000 to $63,000, which disqualifies vehicles like the large luxury sedan that have an ICEV damage of over $10,000 in states like Massachusetts. The Tesla Model S also does not qualify for the federal subsidy. Besides New Jersey, the compact SUV ICEV does not have damages over $7,817 (New York), such that even with a zero emission electric grid, the BEV benefit cannot equal the subsidy ($9,500 in New York). In Colorado, Texas, and Louisiana where there is no MSRP cap, the ICEV damages even for the large luxury sedan do not exceed $6,283, not enough to equal even the federal subsidy of $7,500.

Massachusetts is an example where the climate benefit decreases but the air quality benefit increases with the marginal grid. This could occur if neighboring states use more advanced NO_x and SO_x traps in combined cycle plants to reduce air quality impacts but Massachusetts has higher energy efficiency in its plants.

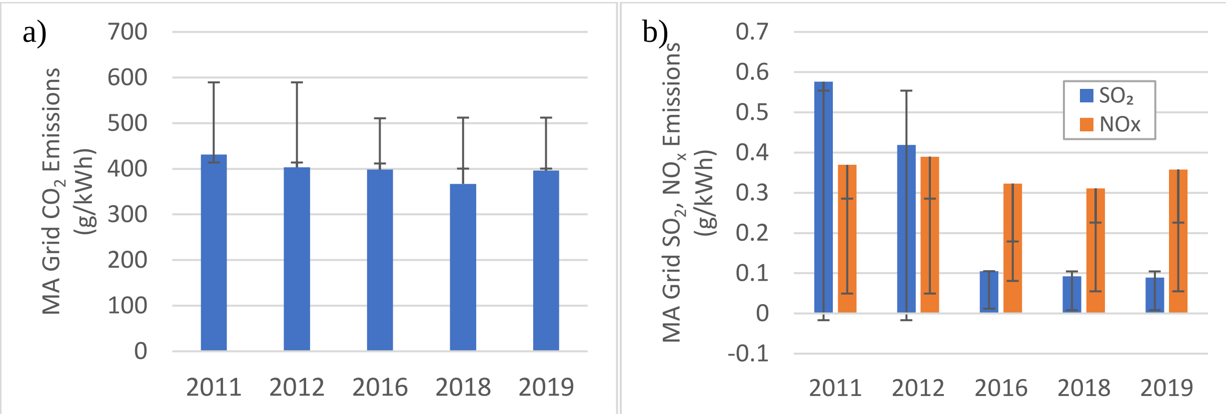


Figure 15 – 2011–2019 state average (bar) and NPCC NERC region marginal grid dispatch model (whisker) (a) CO_2 emissions (b) SO_2, NO_x

Figure 15a shows that CO_2 emission factors have decreased 8% and 9% for state average and NERC NPCC (Northeast Power Coordinating Council) region marginal grids, respectively, from 2011 to 2019 in Massachusetts. The whisker end caps represent the minimum and maximum value for the marginal grid, as it varies by 24 hours a day and three seasonal divisions, and the average value for the marginal grid is used for making percent change comparisons. Except for 2011, even the minimum marginal value is above the state average CO_2 emission factor, leading to a 10% smaller climate benefit for the marginal grid sensitivity case. Figure 15b shows that sulfur dioxide emissions have decreased by 85% and 79% for state average and marginal grids, respectively, for 2011–2019. It is noted that marginal minimum values are negative in 2011 and 2012, and this may be an artifact of the dispatch model source used in this study; these negative values were assumed to be zero for damage calculations. The average of the maximum and minimum marginal SO_2 emission factors is 53 to 37% lower from 2011 to 2019 than the state average grid, resulting in 53% less SO_2 emissions/year for the Hyundai Kona EV. This is a result of the distribution of SO_2 emission factors throughout the hours of the day and seasons, as well as the charging profile used for the Hyundai Kona EV. Nitrogen oxide emissions have decreased 3 and 16% for state average and marginal grids, respectively, for 2011 to 2019 in Massachusetts. Both maxima and minima for the marginal grid are below the average grid value for NO_x, thus resulting in 63% lower emissions annually. The combined impact of the lower NO_x and SO_2 emissions for the marginal grid causes a 12% larger air quality benefit.

From 2011 to 2019 Massachusetts has eliminated coal from its fuel sources and increased natural gas share by 3%, hydro, solar, wind, and nuclear by a net 4% [39] (including a 3% loss in nuclear due to the Pilgrim plant shut down), and biomass and wood burning by 2% as shown in Figure 16. Biomass and wood combustion may be considered carbon neutral for combustion but continue to contribute to air quality damages, while natural gas no longer provides any comparative climate or air quality benefit since coal is phased out and other petroleum such as #2 fuel oil accounts for less than 0.5% of generation.

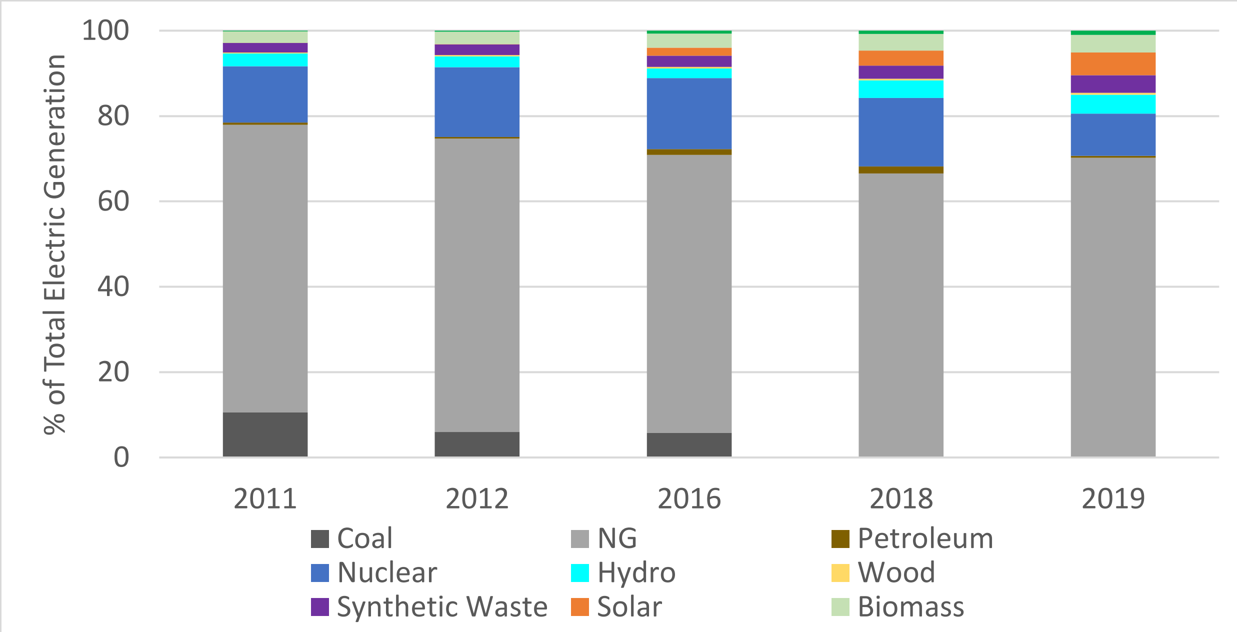


Figure 16 – Massachusetts electric generation fuel sources by %, 2011-2019

4.4 Monetized damages by pollutant

Figure 17 shows the breakout of damages by pollutant for the newest vehicles in the dataset for Massachusetts. Climate impacts are 32–38% of damages for ICEVs for both base and top trims, while ammonia causes 52–58% of damages, due to the larger emission mass for NH_3 among all pollutants by 20–1,062% for the compact luxury sedan (2021 BMW 330i). In addition, the mortality scaling factor for NH_3 in road transport is 3–95 times larger than the other pollutants (refer to section 3.1 and Table 5 for explanation). The next pollutant with the largest impact is $PM_{2.5}$, which is 6–11% of damages for ICEVs, with less than 2% from VOCs, SO_2, and NO_x. The increase in damage from moving to the top trim for ICEVs is shared equally by climate and ammonia, both showing a 56% increase for example in the same BMW. For BEVs, climate impact and ammonia share approximately equal parts of damages of 38%, NO_x causes 15%, $PM_{2.5}$ 6–7%, 3% to SO_2, and the remainder to VOCs. Although $PM_{2.5}$ has a 14 times larger mortality scaling factor than NO_x for electric generation, the grid also outputs 30 times more NO_x in mass than $PM_{2.5}$, thus NO_x becomes more important in Massachusetts for electric generation damages compared to road transport. There is no change in the share of pollutants contributing to the total damage in moving up trim levels for BEVs, because the damage for each pollutant increases linearly with total energy usage for the full useful life of the vehicle. Thus, no separate data is shown in Figure 17 for top trim BEVs.

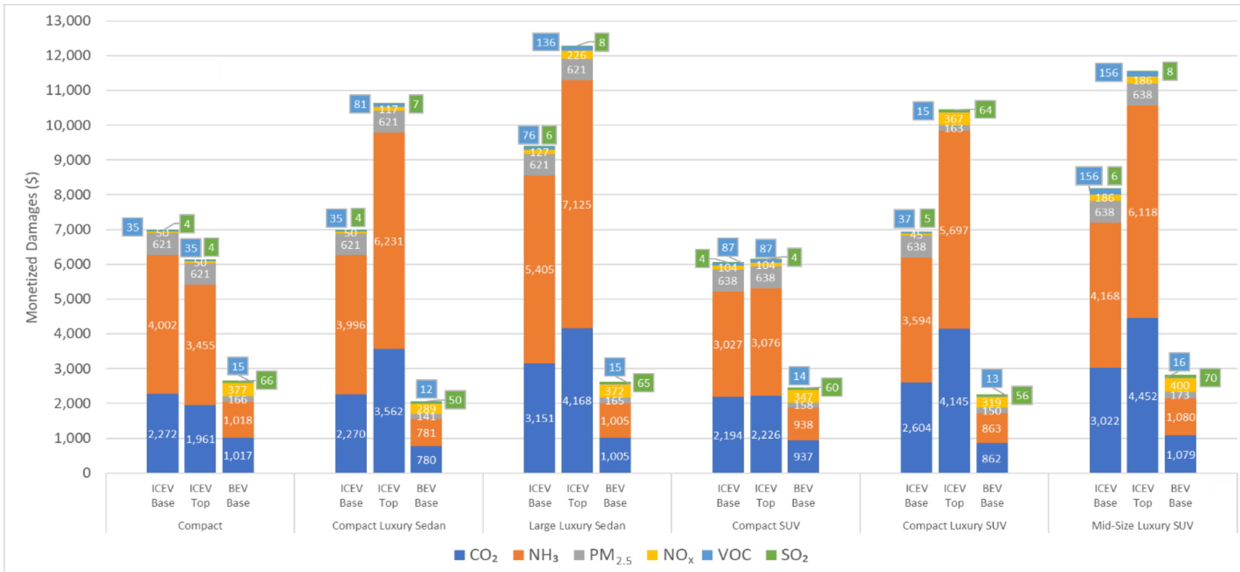


Figure 17 – Monetized climate and air quality impacts of ICEVs and BEVs by vehicle size and trim for newest models in Massachusetts

The analyses thus far show ammonia as a major contributor to air quality damages, yet it is not an officially controlled pollutant for road emissions by the EPA, so it is not a part of the measurements for vehicle certification. Part of the reason is likely since ammonia is seen mainly as a problem for the agricultural sector to address, as it produces 83% of the US total NH_3 emissions according to NEI 2017 [43].

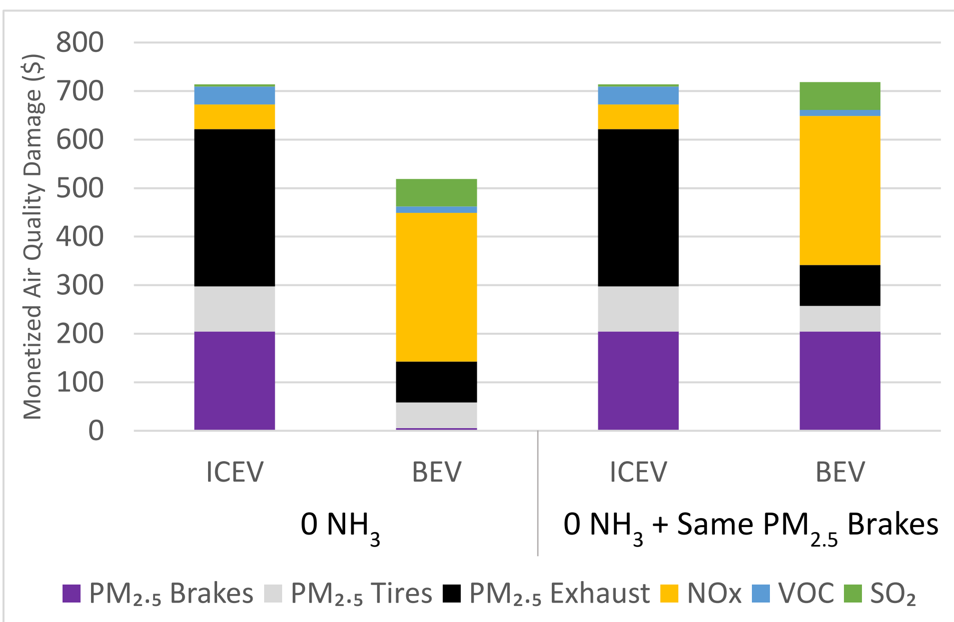


Figure 18 – Massachusetts compact luxury sedan air quality impact with zero ammonia and equal $PM_{2.5}$ brakewear emissions for ICEV and BEV

However, this means the assumption that ammonia scales linearly with CO_2 may not be reliable and cannot be verified for specific vehicles, unlike NO_x and $PM_{2.5}$ which the government requires vehicles to be tested to meet certain levels. Thus, if we assume the ammonia estimates are too unreliable to use and do not consider them at all, the BEV air quality benefit for the compact luxury sedan is reduced by 63% from $525 to $195. In addition, the $PM_{2.5}$ emission from brakewear accounts for 33% of the total $PM_{2.5}$ emissions from a 2021 BMW 330i including tirewear and exhaust emissions. In a BEV, it is assumed that brakewear $PM_{2.5}$ is 5% of that in an ICEV. If the brakewear is assumed to be the same for both ICEV and BEV instead, as done in Holland et al., [11] the air quality impact of the ICEV and BEV are now within 0.7%, as shown in Figure 18.

4.5 Monetized damages by region and road type

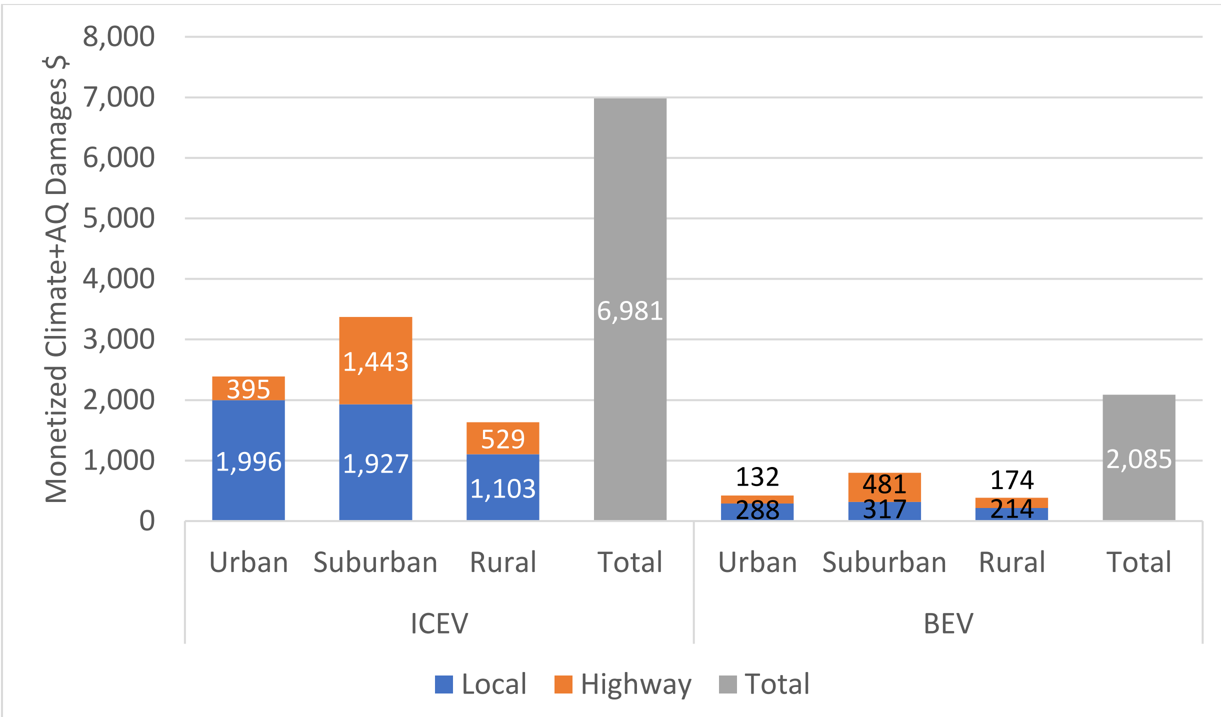


Figure 19 – Monetized climate and air quality benefit by region and road type (NY)

The damage split across urban, suburban, and rural regions in New York is 36%, 45%, and 19%, respectively for ICEVs, and 33%, 45%, 22%, respectively for BEVs as shown in Figure 19, using the compact luxury sedan base trim as an example. The larger proportion of damages from urban driving for ICEVs comes from higher efficiency in highway (rural) driving, as low engine speed and part load at steady cruise consumes less fuel than higher engine speeds, varying and higher loads, and braking on urban roads. The opposite is true for BEVs, where energy consumed increases with vehicle speed, such that highway driving is less efficient, and urban driving also has the advantage of regenerative braking recouping power back into the battery. This is shown in Figure 20 for both base (bar) and top (whisker) trims. Although not directly visualized, the combined cycle efficiency for suburban local road driving is 55% city and 45% highway cycle, and thus lies approximately in the middle between the city and highway cycles.

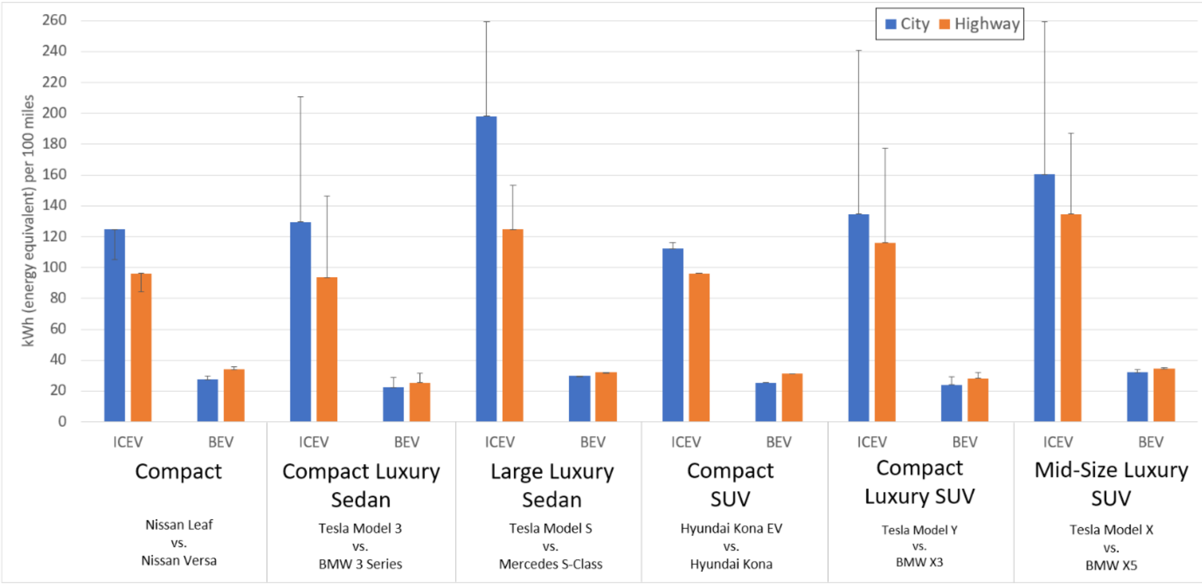


Figure 20 – EPA City and Highway cycle vehicle energy consumption (kWh/100 miles)

This is also reflected in the share of damages from local and highway driving, where the damage split is 71% and 55% for urban and suburban local roads respectively for ICEVs, and 65% and 52% for BEVs; more damages are proportionally from highways than local roads. The damage split across regions changes in states like Wyoming where 7,771 miles of the 11,104 annual miles are allocated to rural roads based on VMT, and the BEV is less efficient than in urban roads in New York. The damages are allocated 20%, 13%, and 67% for ICEVs and 16%, 11%, 73% for BEVs in Wyoming for urban, suburban, and rural regions respectively.

4.6 Monetized exported air quality damages of driving a BEV over an ICEV

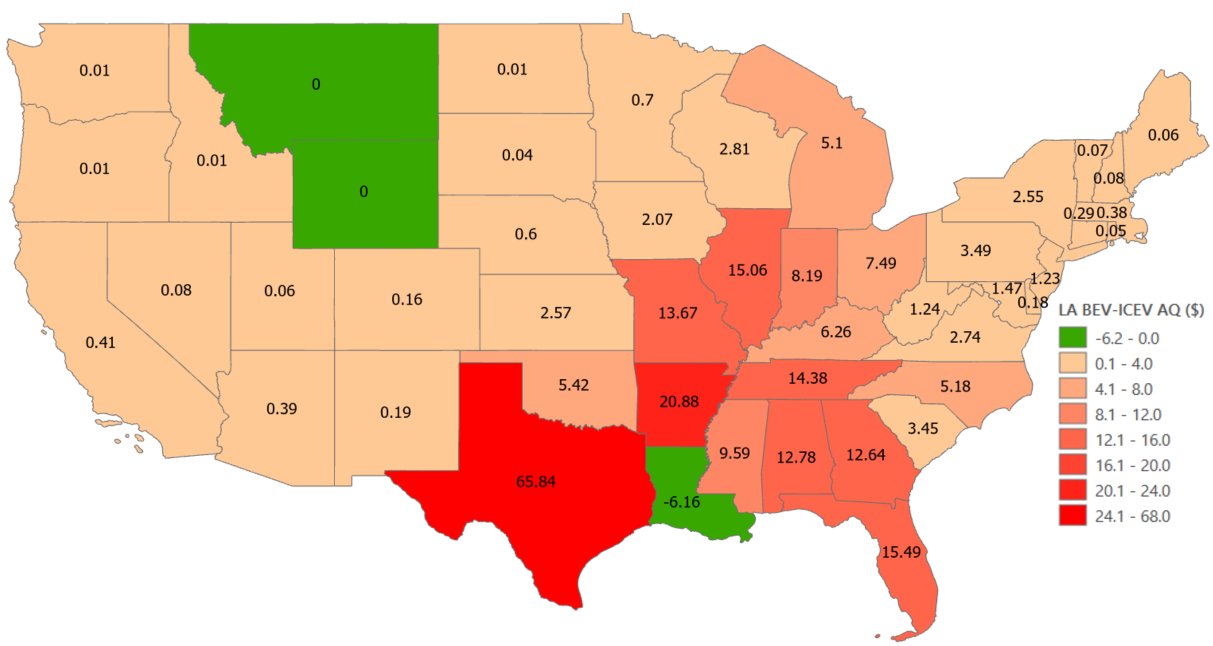


Figure 21 – Exported air quality damages (BEV – ICEV) of driving a 2021 Hyundai Kona EV over a 2022 Hyundai Kona 2.0L FWD in Louisiana for full useful life (173,151 miles)

Air pollution from a state can travel downwind to different states, causing air quality damages in neighboring. One example of this is comparing the change in air quality damages when switching from an ICEV to a BEV (or BEV – ICEV) in Louisiana. Figure 21 shows that the home state of Louisiana where the BEV is driven decreases its air quality damages by $6 while increasing it by $66 in neighboring states like Texas. The air quality impact across all states from Louisiana increases from $586 to $825 when switching from the 2022 Hyundai Kona 2.0L FWD to 2021 Hyundai Kona EV, and the share of exported damages of the total increases from 47% to 63%. Thus, the combination of the location of roads driven compared to the power plants, population densities where the emissions affect human health, the higher emission factors of the electric grid versus the ICEV all contribute to $245 higher exported air quality damages to outside states with a reduction in the home state. In addition, emissions from power generation are transported further from the point of origin due to the higher height of the smoke stacks compared to the ground level emissions from ICEV exhausts. Louisiana offers a tax incentive of 10% of the MSRP or $2,500, whichever is smaller. The 2021 Kona EV is $38,565 including destination, thus the credit would be $2,500 as 10% is higher than the maximum threshold. With the subsidy, the Louisiana state government then may be encouraging clean up of the air quality within its own borders while increasing early deaths in neighboring states.

5. Summary and conclusions

In this thesis, I find that driving a new base model compact SUV, a 2021 Hyundai Kona EV instead of a 2022 Hyundai Kona 2.0L FWD for its full useful life of 173,151 miles, is an average $1,212 benefit for climate in 46 states ($163 KY – $2,115 VT), $1,555 for air quality benefit in 32 states ($22 ID – $10,927 NJ), and $2,391 combined benefit in 42 states ($301 MT – $12,530 NJ). It is an average -$83 climate benefit (or $83 damage) in 2 states (-$35 WV – -$131 WY), -$433 air quality benefit in 16 states (-$62 ME – -$852 NE), and -$335 combined benefit in 6 states (-$54 WI – -$768 WY). Of the 16 states with air quality damages, 14 of them had an average $830 climate benefit. Except for New Jersey, the benefit is smaller than the combined federal and state subsidy by an average $6,320 across all other states. In states where there are BEV damages over an ICEV, there is no state subsidy. ICEV climate damages vary by up to 6% across the US while ICEV air quality damages vary by up to 194%, and BEV climate and air quality impacts vary by up to 199% and 179%.

I find that changing to a new top trim large luxury sedan, a 2021 Tesla S Performance and a 2020 Mercedes-Benz S65 AMG, changes BEV benefits (or damages) to be an average of 3.8 times larger than those of the 2021 Hyundai Kona, due to minimal penalties in efficiency for increasing power in BEVs compared to ICEVs. The combined benefit is positive in all states with the top trim large luxury sedan class. All other vehicle classes with available BEVs today fall in between the compact SUV and large luxury sedan. NH_3 dominates the total damages, making up 56% and 37% of impacts for ICEVs and BEVs respectively, due to NH_3 production from TWCs and ammonia slip from SCRs. while climate impacts are second largest at 33% and 38% respectively in Massachusetts, for example. In addition, the marginal grid is not always higher in emission factor than the state average grid, and 40 states still have a combined climate and air quality benefit for BEVs compared to 41 with the state average grid. Also, the difference in damages from brakewear $PM_{2.5}$ for BEVs and ICEVs is significant such that it becomes determinative if ammonia emissions are ignored. The BEV air quality benefit in Massachusetts is reduced from $2,314 to $5 if ammonia emissions are not considered and $PM_{2.5}$ from brakewear is assumed equal for the BEV and ICEV.

The northeast, mid-Atlantic, and west coast states have clear climate and air quality benefits from BEVs and offer the highest state subsidies while midwestern states have small or negative benefits, particularly in air quality. Thus, the existence or absence of state subsidies is relatively well matched to states with large positive or small and negative benefits, respectively, but the amount is currently too large in states that offer it, especially when combined with the federal subsidy.

In addition, the federal subsidy may be encouraging BEV sales in midwestern states leading to climate and air quality damages, highlighting the importance of lowering emission factors of the electric grid. Although the benefits from driving a BEV are currently smaller than the subsidy, this study does not include the effect of credits assisting in BEV early adoption rates to meet goals of higher fleet penetration in the coming decades while BEV costs continue to decline. However, if the electric grid sector makes no progress in lowering emissions to match this transition in the light duty vehicle sector, the gap between the subsidy and benefits will not be reduced. Even with efficiency improvements from mobile (ICEV) to stationary combustion combined cycle natural gas), this effort to transform the light duty vehicle sector and electric transmission network to support the additional load may be reduced to merely shifting emissions from road transport to the electric grid. The distribution of negative to positive BEV benefits across the US shows the importance of synchronizing federal goals with state and NERC region-level targets in grid emissions reduction. Otherwise, it is possible that on a national average basis, the subsidy is well matched to BEV benefit, with low emissions/kWh and mile traveled, but on a regional basis, BEVs continue to adversely impact climate and incur human health impacts from air pollution in the Midwest while exceeding targets in the northeast and west coast.

The future of the federal and state subsidies is uncertain. The Clean Energy for America bill, currently being proposed by the US Senate Finance Committee, would increase the federal tax credit up to $12,500 and eliminate the 200,000 vehicle cap for manufacturers for phase-out [85], reinstating the subsidy for General Motors and Tesla for which the federal credits have expired. The new proposed credit phase-out would be in 3 years after 50% or more of new car sales are EVs. Evaluation of this proposal should take into account the expected progress and regional disparities of the electric grid in reducing emissions to avoid unintended climate and air quality impact increases from BEVs.

Appendix

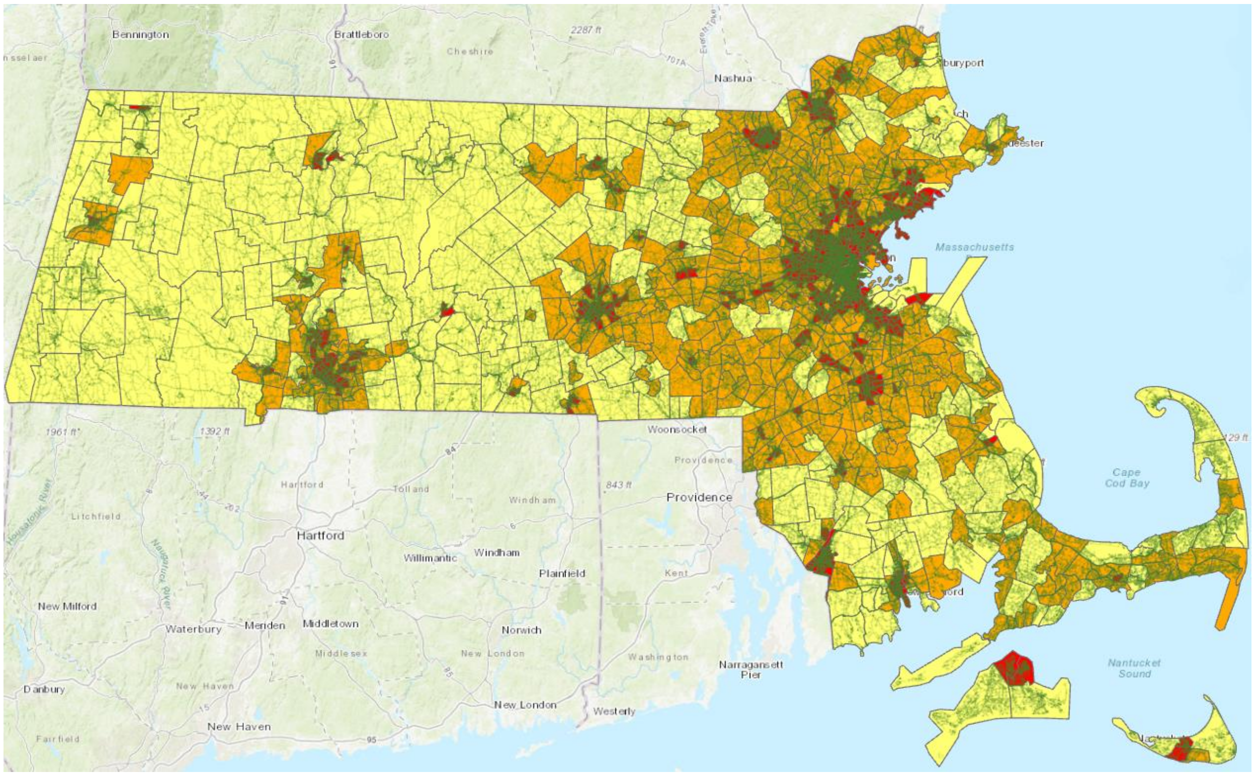


Figure A-1 – Massachusetts census tracts by urban (red), suburban (orange), rural (yellow), and roads (green)

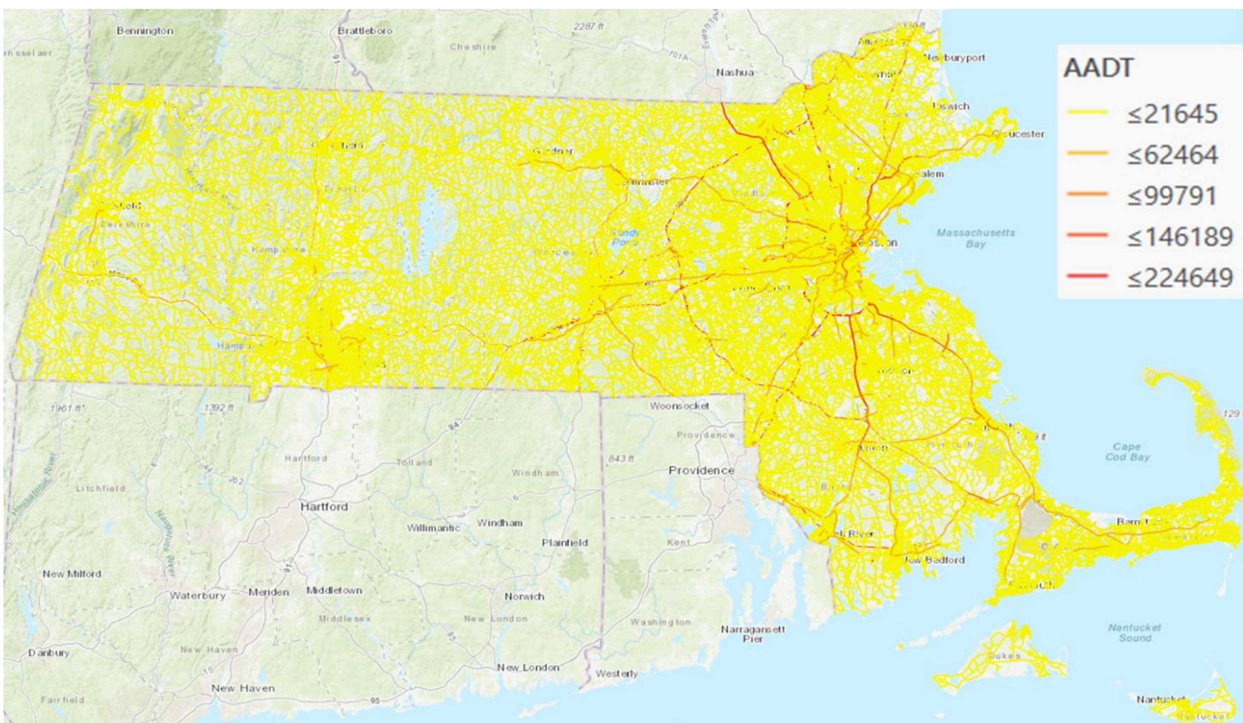


Figure A-2 – Massachusetts roads with AADT

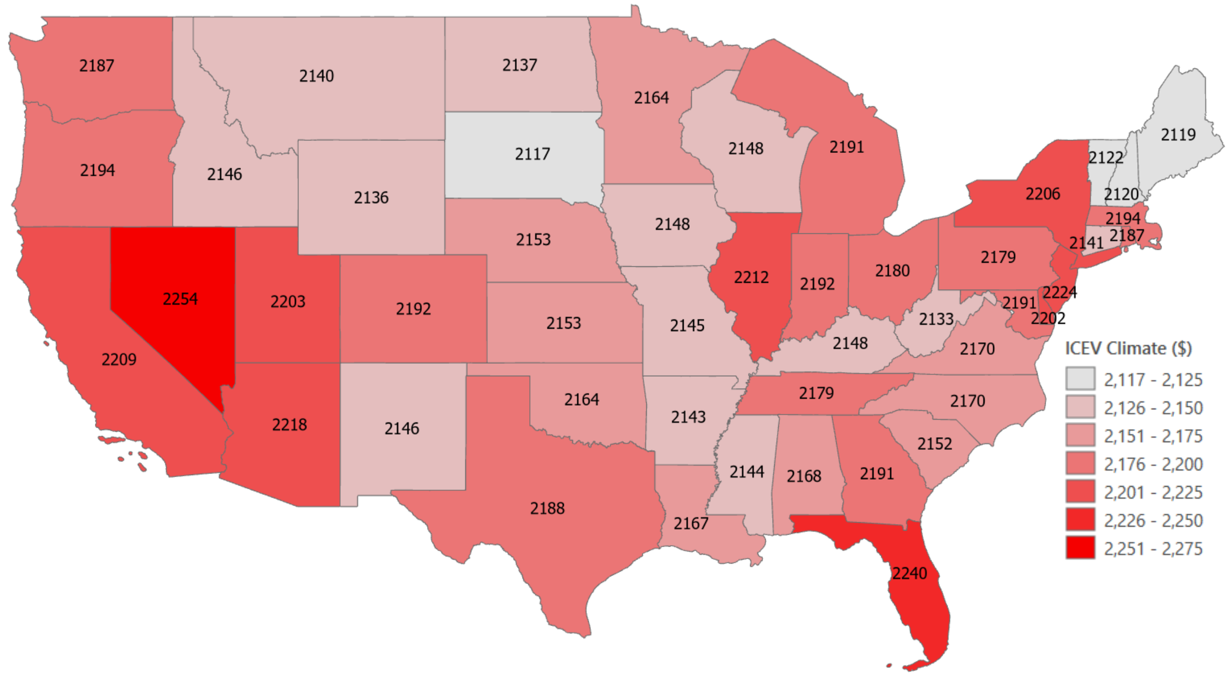


Figure A-3 – Monetized climate damages of driving a 2021 Hyundai Kona 2.0L FWD for 173,151 miles

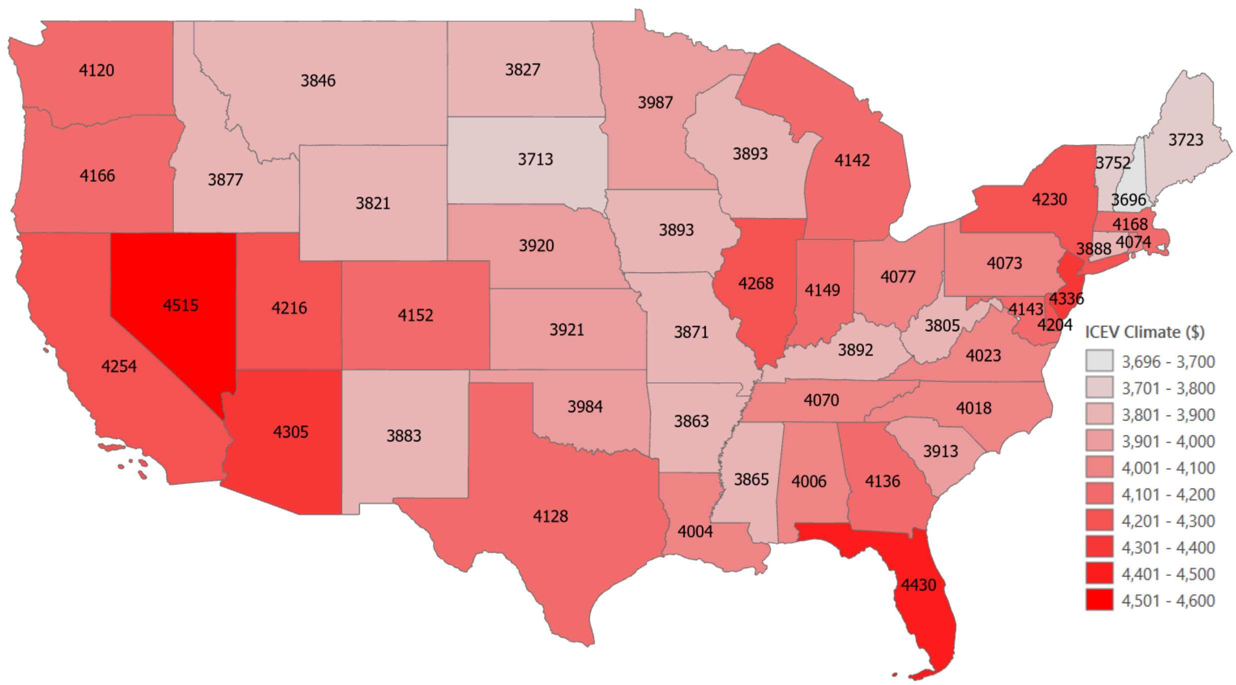


Figure A-4 - Monetized climate damages of driving a 2020 Mercedes-Benz S65 AMG for 173,151 miles

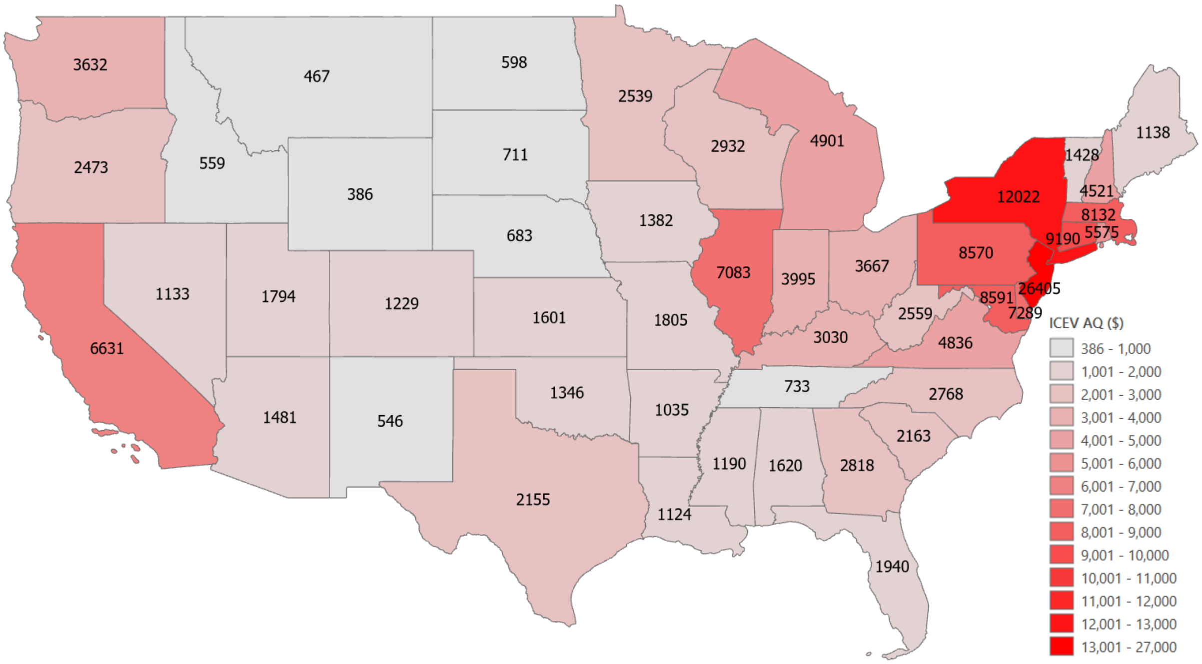


Figure A-5 - Monetized air quality damages of driving a 2020 Mercedes-Benz S65 AMG for 173,151 miles

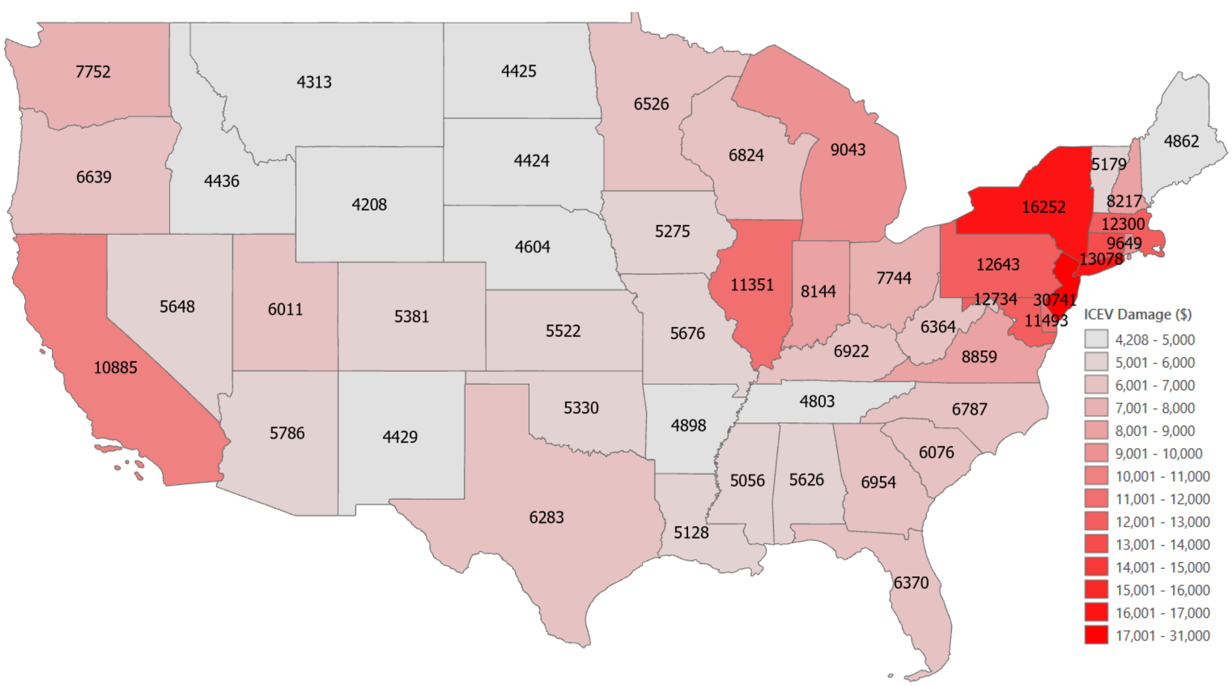


Figure A-6 - Monetized climate and air quality damages of driving a 2020 Mercedes-Benz S65 AMG for 173,151 miles

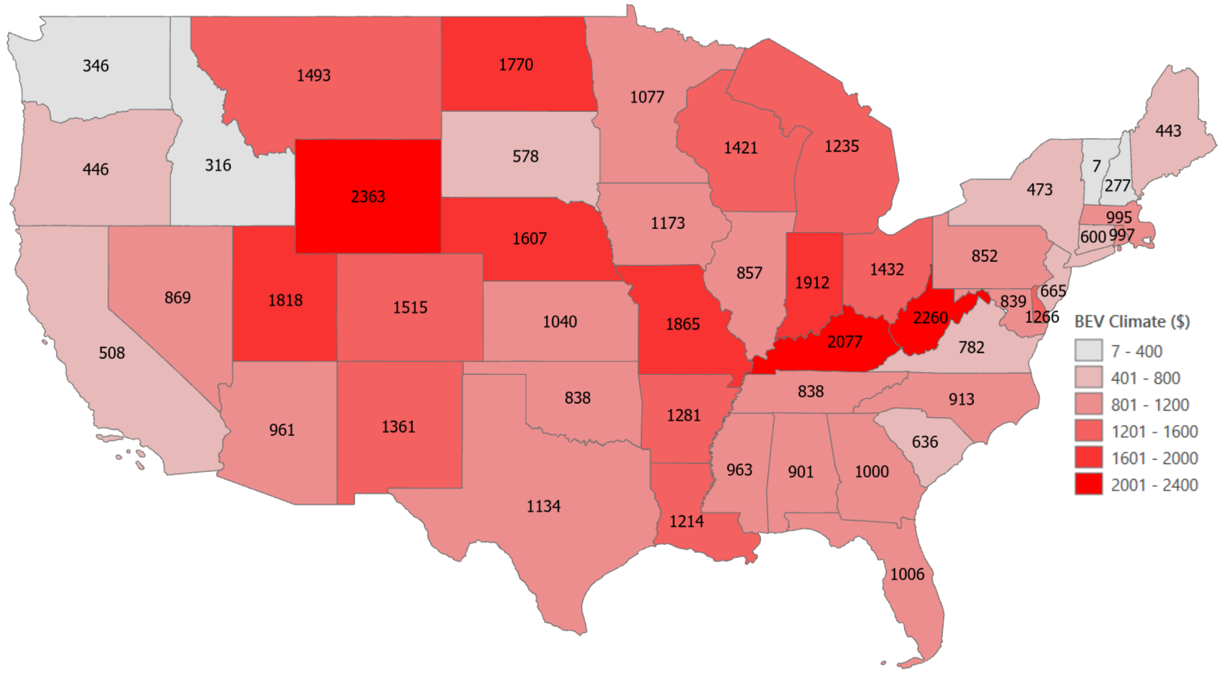


Figure A-7 - Monetized climate damages of driving a 2021 Tesla Model S Performance for 173,151 miles

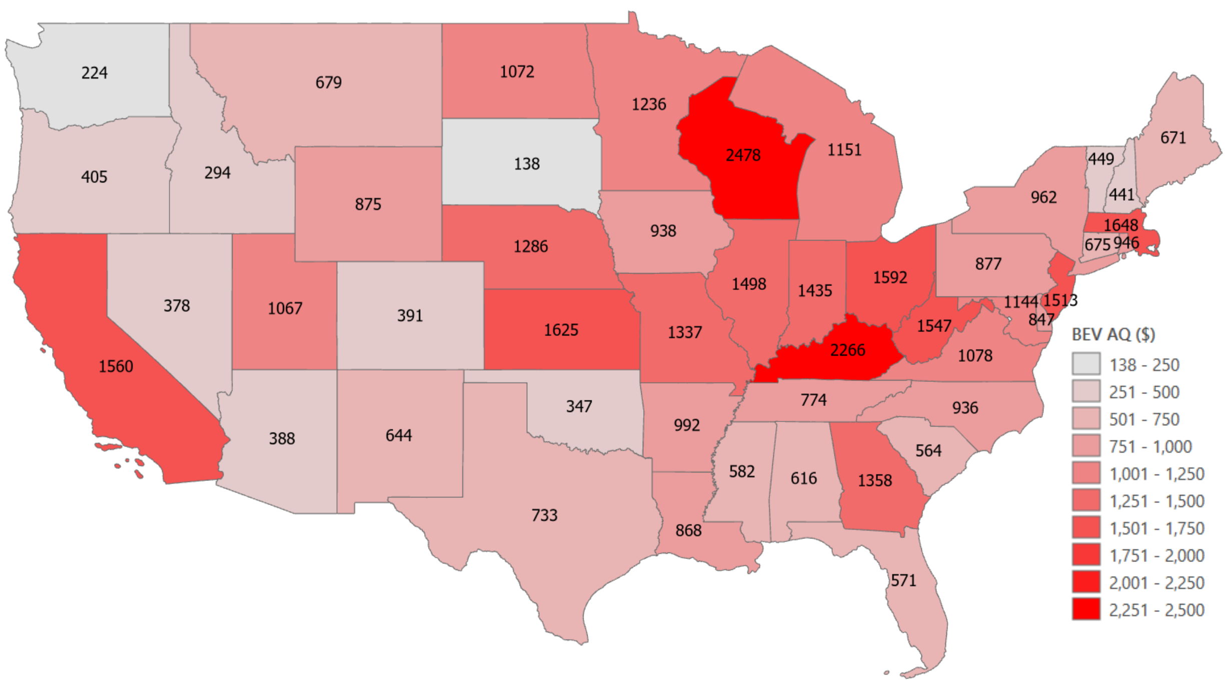


Figure A-8 - Monetized air quality damages of driving a 2021 Tesla Model S Performance for 173,151 miles

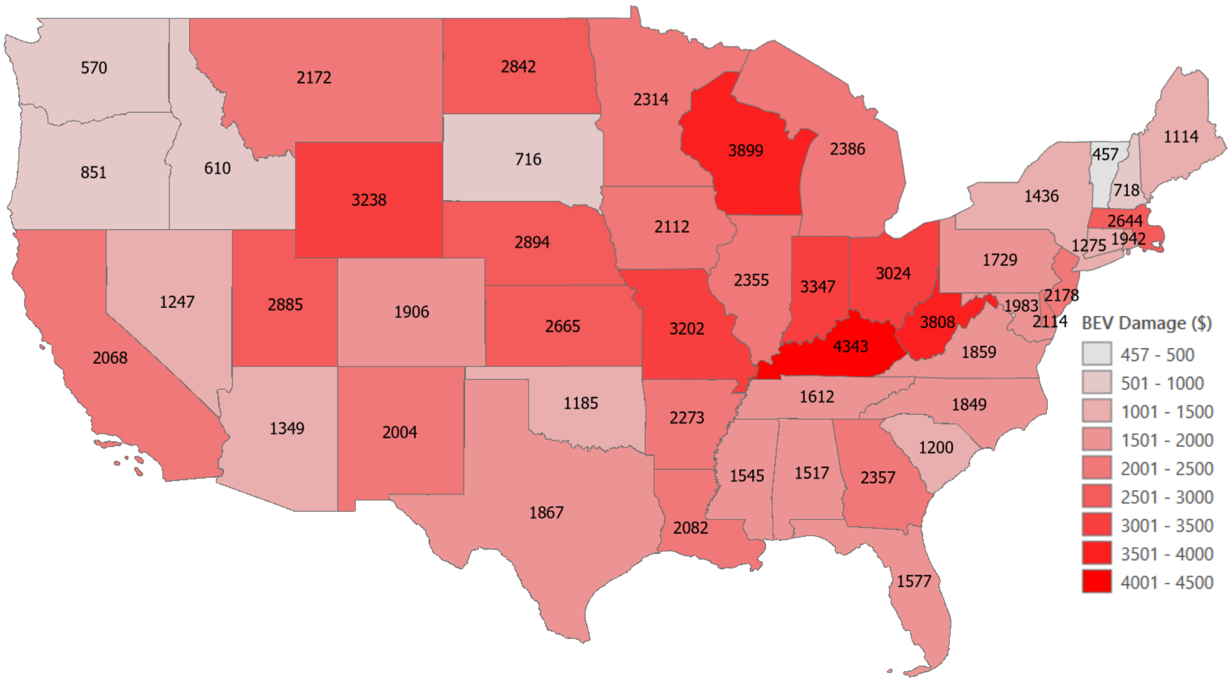


Figure A-9 – Monetized climate and air quality damages of driving a 2021 Tesla Model S Performance for 173,151 miles

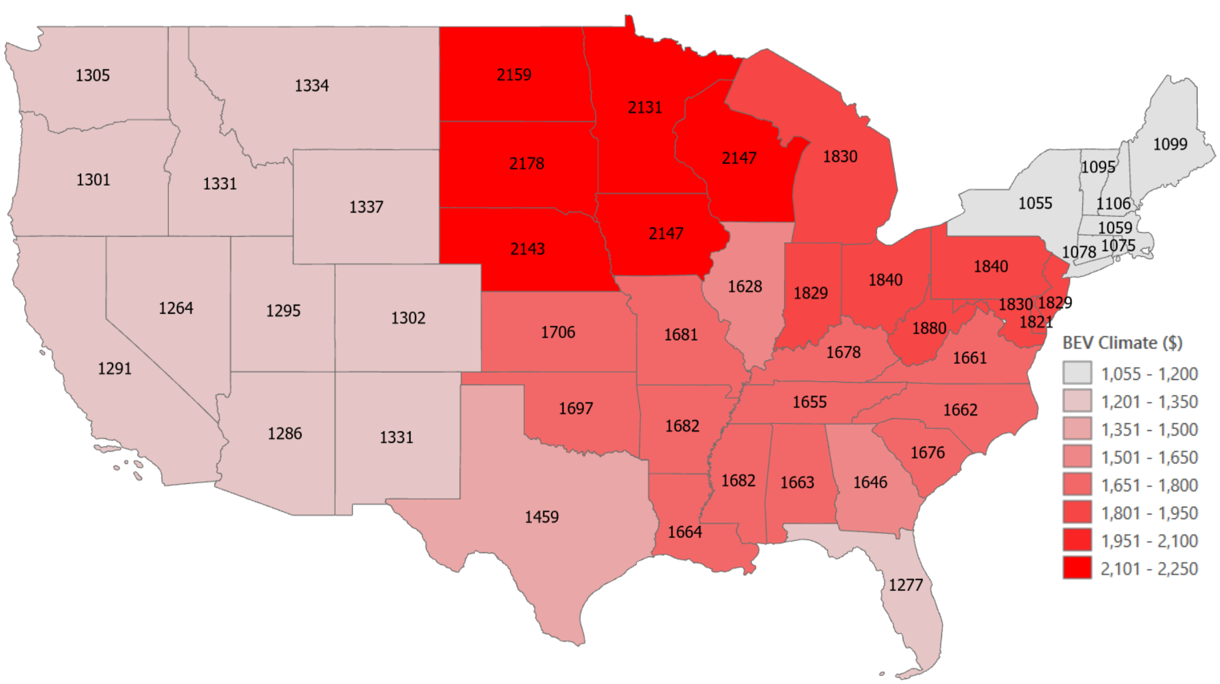


Figure A-10 - Monetized climate damages of driving a 2021 Hyundai Kona EV for 173,151 miles (marginal grid)

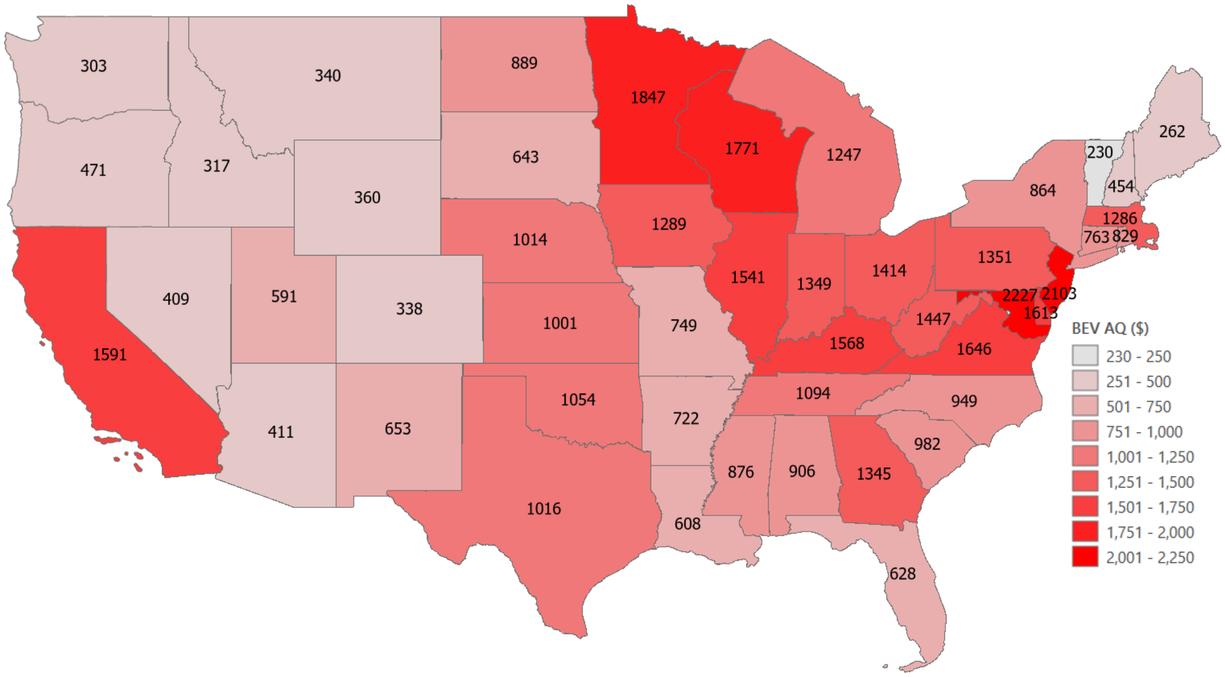


Figure A-11 - Monetized air quality damages of driving a 2021 Hyundai Kona EV for 173,151 miles (marginal grid)

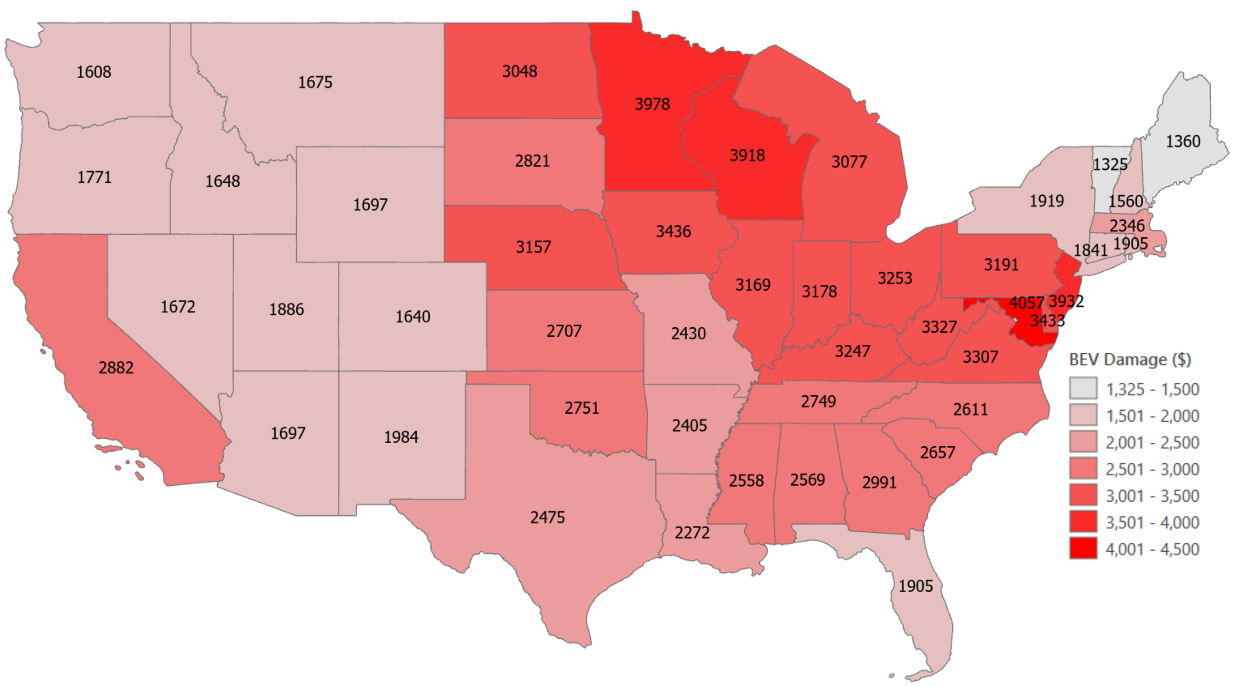


Figure A-12 - Monetized climate and air quality damages of driving a 2021 Hyundai Kona EV for 173,151 miles (marginal grid)

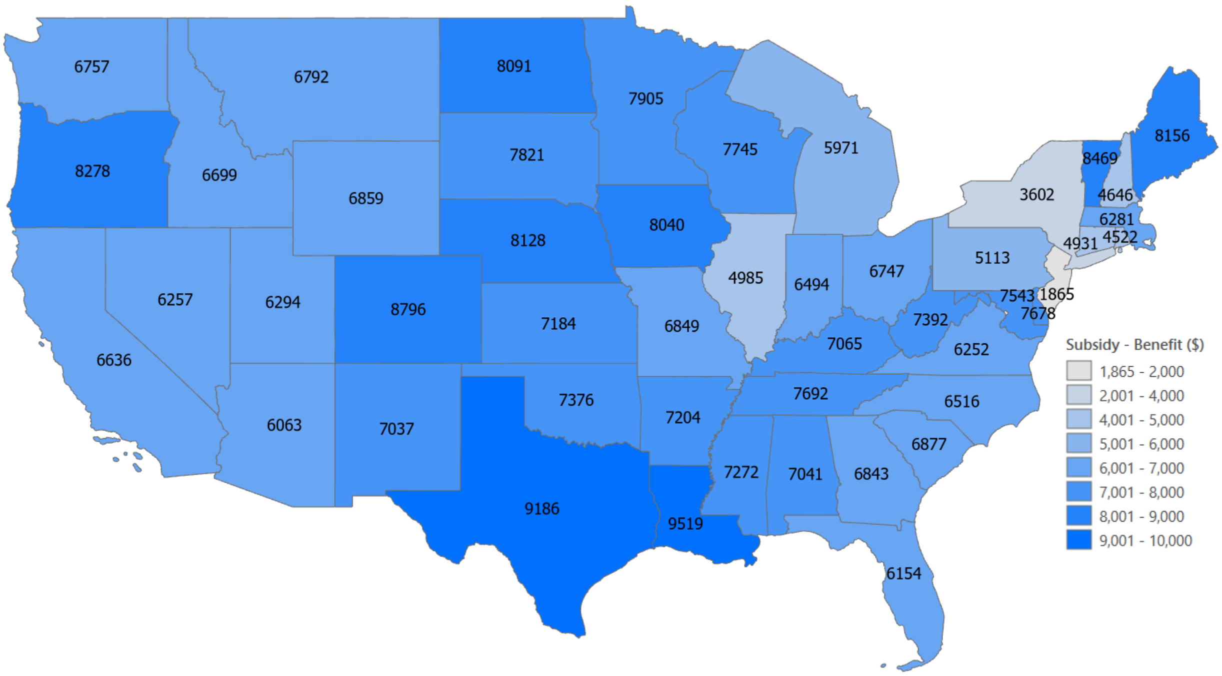


Figure A-13 - Comparison of federal and state subsidies to BEV benefits for 2021 Hyundai Kona, marginal grid (subsidy – benefit).

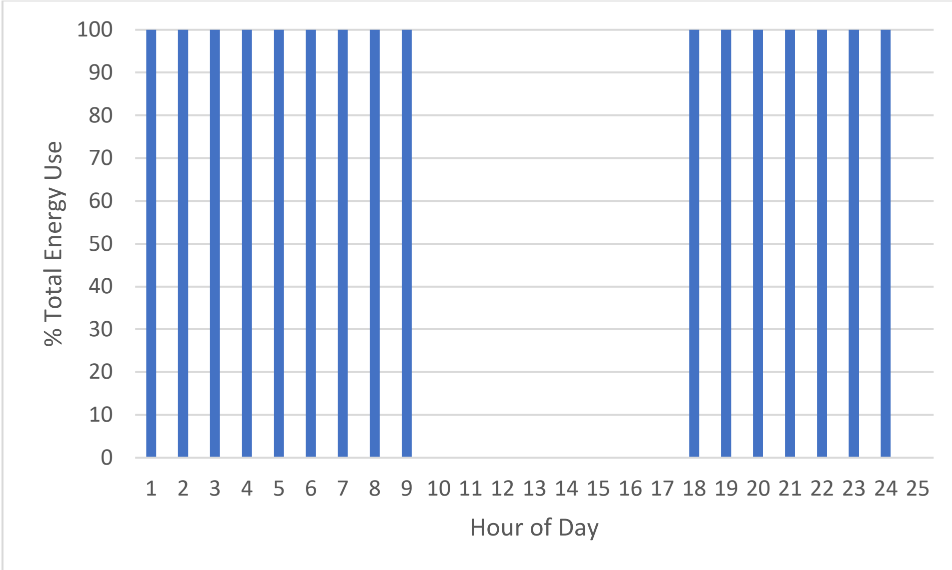


Figure A-14 – 2021 Hyundai Kona EV charging profile @ 2.8kW, 70% capacity refill

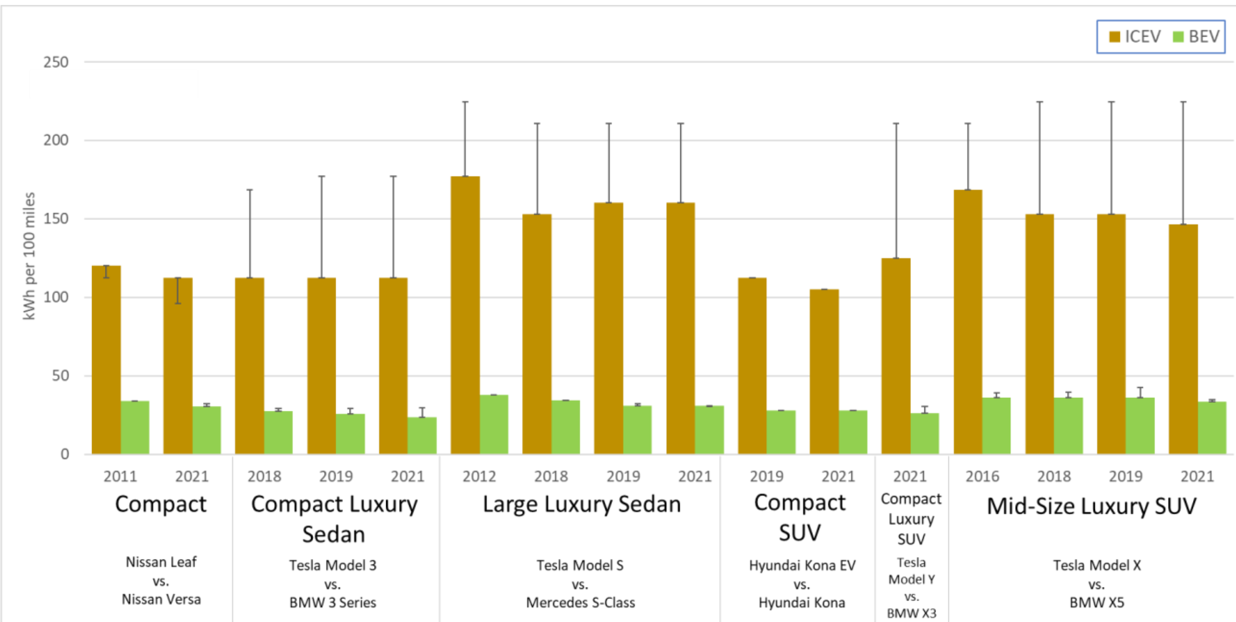


Figure A-15 – Combined cycle efficiency [kWh/100mi] for vehicle type, size, model year, trim (bar=base, whisker=top) in MA

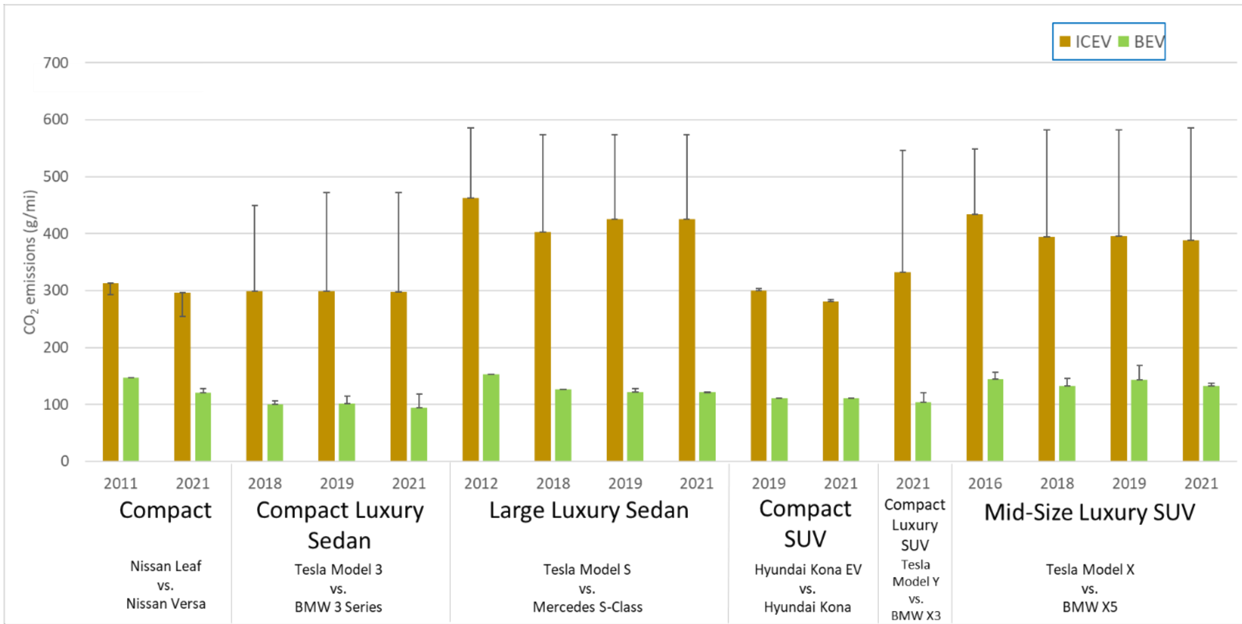


Figure A-16 – Combined cycle CO_2 emissions [g/mi] for vehicle type, size, model year, trim (bar=base, whisker=top) in MA

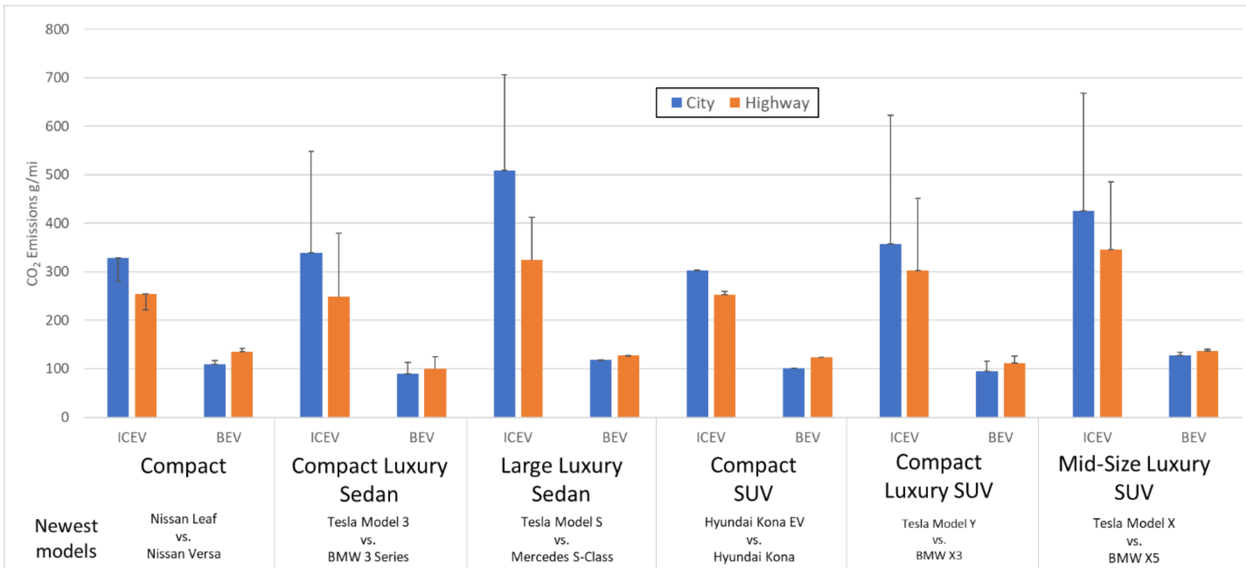


Figure A-17 – City and highway cycle CO_2 emissions [g/mi] for vehicle type, size, trim, newest model (bar=base, whisker=top) in MA

Figure A-18 - Combined cycle NO_x emissions [g/mi] for vehicle type, size, model year, trim (bar=base, whisker=top) in MA

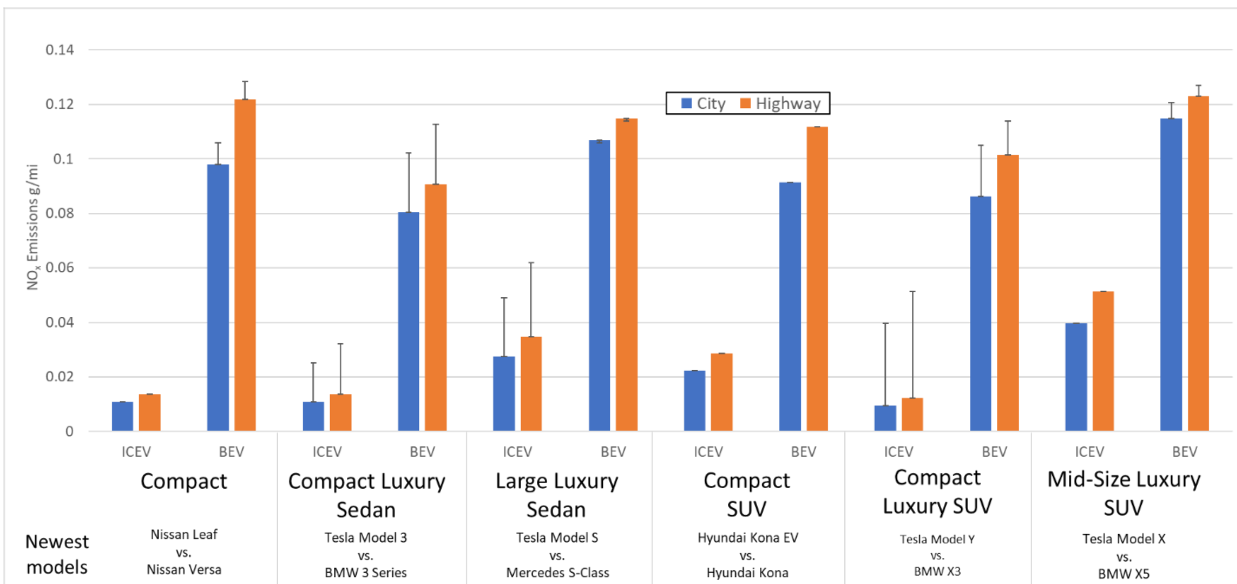


Figure A-19 - City and highway cycle NO_x emissions [g/mi] for vehicle type, size, trim, newest model (bar=base, whisker=top) in MA

Figure A-20 - Combined cycle SO_x emissions [g/mi] for vehicle type, size, model year, trim (bar=base, whisker=top) in MA

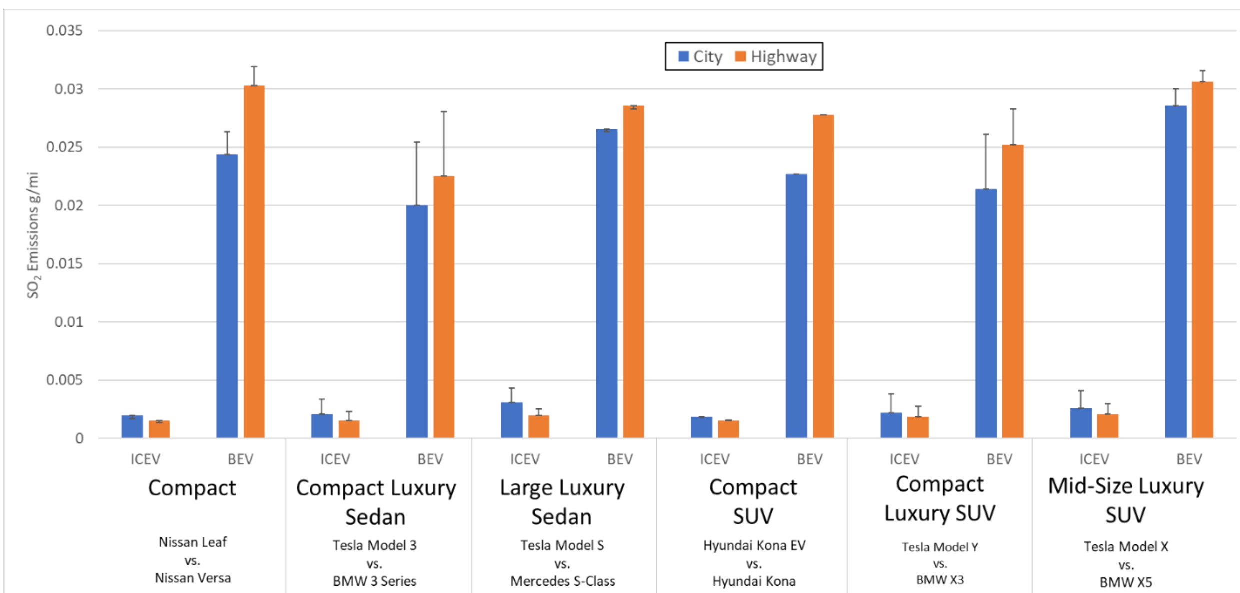


Figure A-21 - City and highway cycle SO_x emissions [g/mi] for vehicle type, size, trim, newest model (bar=base, whisker=top) in MA

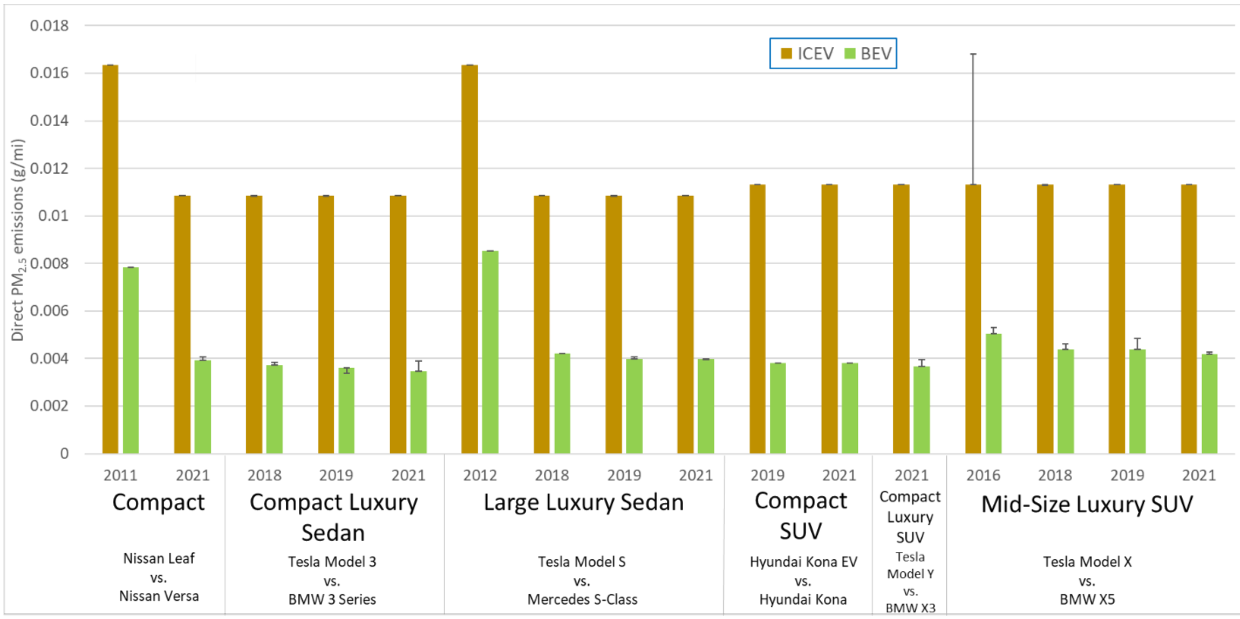


Figure A-22 - Combined cycle $PM_{2.5}$ emissions [g/mi] for vehicle type, size, model year, trim (bar=base, whisker=top) in MA

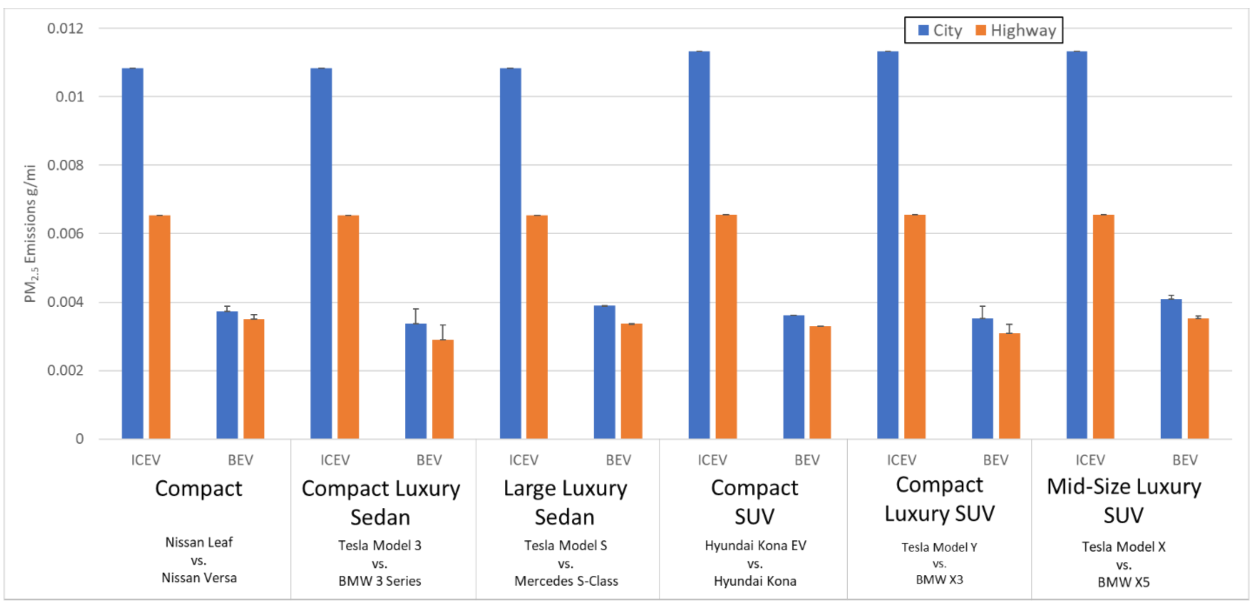


Figure A-23 - City and highway cycle $PM_{2.5}$ emissions [g/mi] for vehicle type, size, trim, newest model (bar=base, whisker=top) in MA

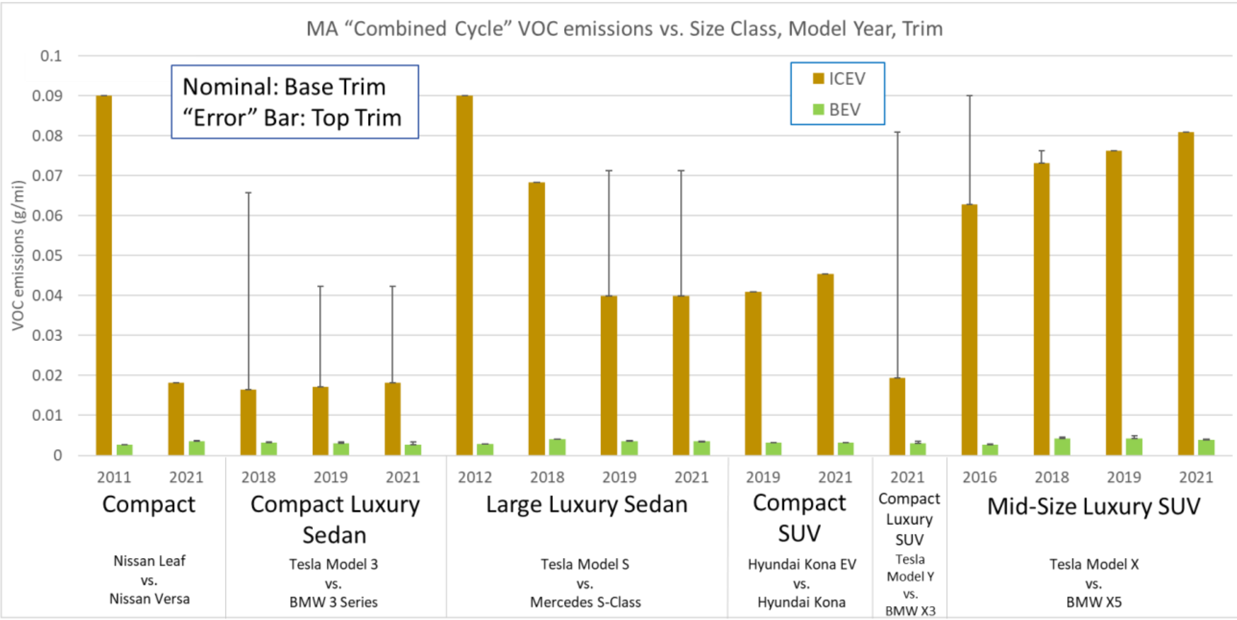


Figure A-24 - Combined cycle VOC emissions [g/mi] for vehicle type, size, model year, trim (bar=base, whisker=top) in MA

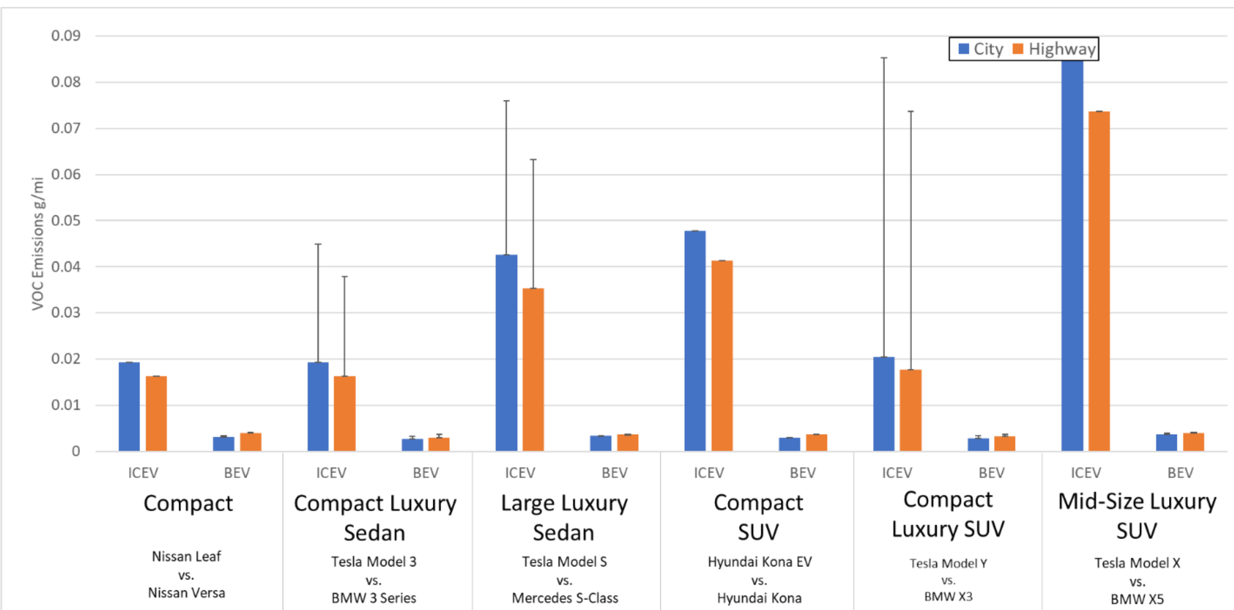


Figure A-25 - City and highway cycle VOC emissions [g/mi] for vehicle type, size, trim, newest model (bar=base, whisker=top) in MA

Figure A-26 - Combined cycle NH_3 emissions [g/mi] for vehicle type, size, model year, trim (bar=base, whisker=top) in MA

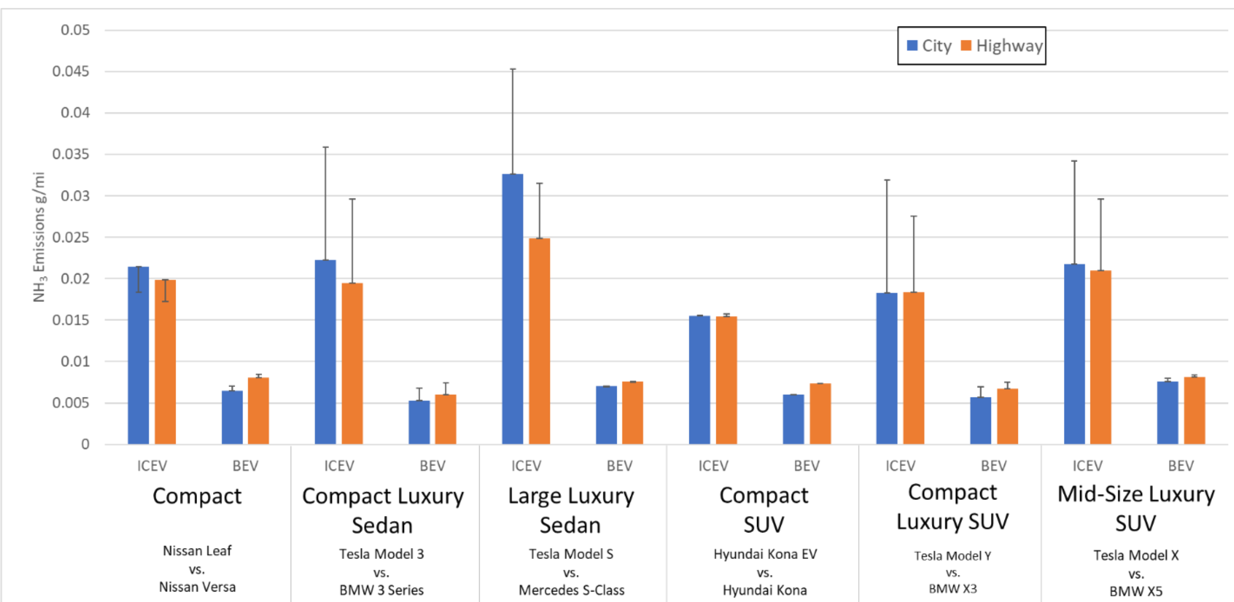


Figure A-27 - City and highway cycle NH_3 emissions [g/mi] for vehicle type, size, trim, newest model (bar=base, whisker=top) in MA

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