Carbon Footprint Comparison between Electric and Gasoline Powered Vehicles, the Real Truth

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***Abstract*—There are many arguments for the introduction of electric and hybrid electric vehicles into the economy compared to standard gasoline vehicles. Many of these arguments involve the idea that these electric vehicles significantly reduce or completely eliminate carbon emissions. Other arguments involve the idea that pollution negatively affects health and that electric vehicles can reduce these negative effects. This paper primarily focused on carbon emissions, but has also investigated the health benefits of reduced carbon emissions. When research into the literature was done, it was determined the health benefits were negligible. In some cases, pollution emissions increased due to the use of electric vehicles. Similarly, only a 10% reduction in carbon emissions was found for the overall lifecycle of electric vehicles or 67,000 kg CO_2 and 60,000 kg CO_2 for gasoline vehicles and electric vehicles, respectively. When a perturbation analysis was completed, emission reduction was found to range between -20% and +20% based on the literature data used. Further exploration into the literature must be done to reduce the uncertainty in the data and to come to a more reasonable conclusion.**

Introduction

When comparing the carbon emissions of Electric Vehicles (EVs) and Gasoline Vehicles (GVs), many studies only focus on the on-road emissions only which is simply not correct. The batteries of the electric vehicles must be charged. Thus, the emissions from the power grid used to charge the (EV)'s battery must be considered. Further, the type of power plant must be addressed as some power plants still burn coal with significant carbon emissions. When investigating a combined system, the EV along with the power plant can in many cases produce more carbon emissions than a high efficiency gasoline vehicle. Still further, quite often in many studies, many researchers do not consider the environmental impact of mining and manufacturing the material to create the (EVs) in comparison to (GVs). The following effects must be considered:

1. Mining operations can disturb the natural ecosystems and, in some places, can cause mass deforestation which reduces the Earth's ability to remove CO_2 from the atmosphere. Plants are the natural Earth air filters.
2. Depending on the manufacturing process, significant amounts of waste products and other hazardous waste can be produced.

   Manufacturing also requires substantial amounts of electrical energy, usually produced from fossil fuels and in particular coal which release CO_2 and other toxic pollutants into the atmosphere.

For these reasons, it is important to look at the carbon emissions and environmental impact of mining, manufacturing, and operation of (EVs) compared to (GVs).

When looking at mining, it is important to not only look at the direct emissions due to mining equipment and raw material
transportation but to also look at indirect emissions such as deforestation. Deforestation and other effects on plant life increase CO_2 in the atmosphere by reducing the Earth's natural ability to remove CO_2 from the atmosphere. This phase is commonly targeted by climate activists primarily because of the issue of deforestation, but it is usually not linked directly to the final product which in this case is the automobile.

Less considered by the general public is the manufacturing phase. This phase is important because a considerable amount of energy is needed for refining raw materials, creation of parts, and assembly of the vehicle. This energy requirement is usually met by burning coal, natural gas, and other common fossil fuels. Often, this phase and the mining phase are combined in an approach called the Well-to-Wheel approach. This is the case in this paper; however, the mining phase will be kept to exclusively analyze the effect of deforestation as a direct result of mining.

The operation phase will be the primary focus in this paper. Direct emissions as well as indirect emissions will be considered to understand and quantify the differences between (EVs) and (GVs). Direct emissions will include exhaust emissions from the tailpipe of the vehicle in the case of (GVs) and (HEVs). These types of emissions are sometimes called road emissions. Indirect emissions will include power plant emissions in the case of (EVs) and hybrid electric vehicles (HEVs).

The last phase that will be considered is the recycling phase. Once an automobile is no longer in use, it be moved to a scrap yard to be recycled. This phase will allow for the mitigation of CO_2 from the mining phase.

Mining

Mining is the first step in the process of creating (EVs) and (GVs). Mining has the potential to cause significant amount of pollution due to mining equipment, hazardous runoff, and deforestation. Here, it is assumed that the effect of deforestation is the primary driver for carbon and pollutant emissions in the mining phase. To assess the effects of mining, a quantitative measurement scale is needed. Total Material Requirement (TMR) will be used as the standard scale for this paper. As can be seen in the figure 1 below, (EVs) require almost three times the (TMR) in certain categories as (GVs).

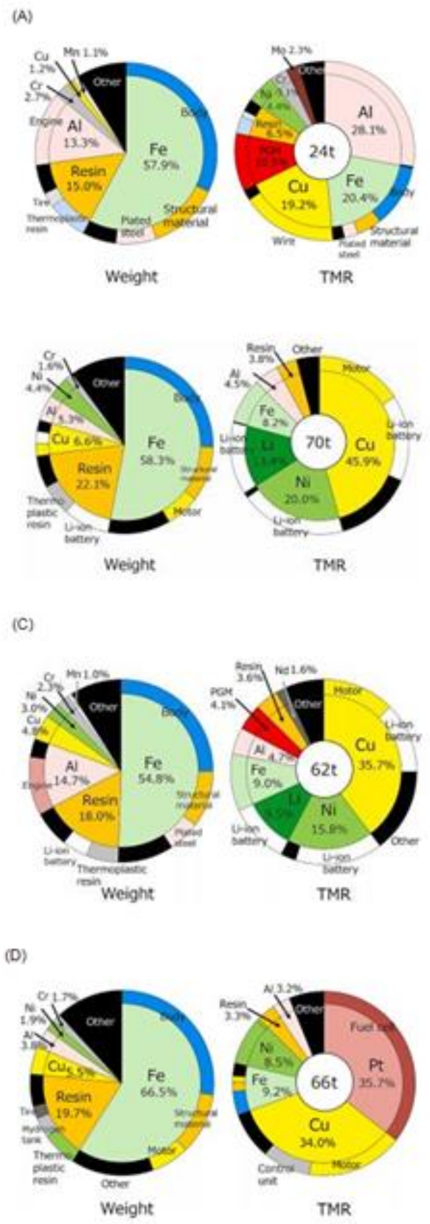

Figure 1: Weight and (TMR) for different automobile types. (A) Gasoline Vehicles, (B) Electric Vehicles, (C) Hybrid Electric Vehicles, (D) Fuel Cell Vehicles. [1]

The materials primarily responsible for this increase in (TMR) are Cu, Ni, and Li. It is seen that approximately half of the (TMR) for (EVs) and (HEVs) is used to produce batteries. Despite consuming half of the (TMR), Cu, Ni, and Li make up less than 10% of the vehicles total weight. When comparing the (GVs), about half the (TMR) comes from Al and Fe, and Al and Fe comprise 70% of the total weight. This excess partially explains the significant difference in the (TMR) of (GVs) and (EVs).
Considering maintenance, the maintenance effect on emissions for (EVs) and (HEVs) is markedly higher than that for (GVs). This is because a significant amount of (TMR) is needed if the lithium-ion batteries need to be replaced whereas for a (GV) less (TMR) less (TMR) is needed if the engine needs to be repaired or if the lead acid battery needs to be replaced battery needs to be replaced.
The operation phase is the largest contributor of (TMR) in the case of (GVs). It is suspected that recycling processes could reduce the amount of energy required to refine aluminum and steel by 97% and 65% respectively, which would further increase the (TMR) gap between (EVs) and (GVs). [1] Maintenance effects will be further considered in the operation stage of the automobile.

Deforestation

Focusing on the deforestation impacts of mining aluminum, iron, lithium, nickel, and copper, as well as fuels such as coal and natural gas used in the production and operation phases, allows the start of an understanding of the carbon footprint of the mining phase of vehicle production. The first step is to find the largest producers of these materials. The main producers of these materials are Chile, China, Australia, and Indonesia. [2], [3]
Exploring the deforestation of countries in Indonesia such as India, data shows that districts that produce iron, aluminum and coal saw between 350 km^2 and 450 km^2 more deforestation than those that did not produce the same material. [4]

Table 1: Iron production and Forest area change in different districts in India [4]

State Name	District Name	Iron production (MT)	Forest Area Change (km^2)
ODISHA	KENDUJHAR	55.45	-2.82
ODISHA	MAYURBHANJ	1.17	2.13
ODISHA	SUNDARGARH	19.59	-2.68
CHHATTISGARH	DANTEWAD	22.55	-8484
CHHATTISGARH	KANKER	0.333	-22.41
CHHATTISGARH	RAJNANDGAON	0.001	-8.53
JHARKHAND	WEST SINGBHUM	22.55	0
TOTAL		121.644	-8307.44

MT is million tons. With a correction factor of 0.907 based on a statistical analysis, the deforestation per ton of iron production is $7.735* \ 10^{-5} \ km^2/t$ where t is ton. The average global iron and aluminum production is expected to produce a similar amount of deforestation. The deforestation due to copper mining in China in the 1700s and 1800s is given by the following equation. [5]

$$y = 0.00025x - 0.811$$

Where y is deforested area in km^2, and x is copper produced in jin (1 jin = 597 g). Converting to US tons,

$$y = 0.380x - 0.811$$

Where y is deforested area in km^2, and x is now copper produced in US tons.
With the improvement of mining technology in the recent centuries, this is predicted to be orders of magnitude larger than deforestation due to copper mining today. Assuming a scaling factor of 1000, the following equation is obtained.

$$y = 3.80 \cdot 10^{-4}x - 8.11 \cdot 10^{-4}$$

This expression is comparable to the deforestation from iron production.
If the deforestation due to mining lithium and nickel is neglected for this simple analysis, an estimate for deforestation for (GVs) and (EVs) is obtained.

Table 2: Total deforestation due to mining

Vehicle Type	Material	Weight (t)	Deforestation per material (km^2)
GV	Iron	4.9	$3.79*10^{-4}$
	Aluminum	6.7	$5.18*10^{-4}$
	Copper	4.6	$9.37*10^{-4}$
	Total Deforestation (km^2)		$18.34*10^{-4}$
EV	Iron	5.7	$4.41*10^{-4}$
	Aluminum	3.2	$2.48*10^{-4}$
	Copper	32.1	$114*10^{-4}$
	Total Deforestation (km^2)		$121*10^{-4}$
HEV	Iron	5.6	$4.33*10^{-4}$
	Aluminum	2.9	$2.24*10^{-4}$
	Copper	22.1	$75.9*10^{-4}$
	Total Deforestation (km^2)		$82.5*10^{-4}$

The next question is how much CO_2 is being released into the atmosphere as a direct result of this deforestation. According to the US EPA, 0.82 metric tons of CO_2 per acre are removed annually by forestry. Assuming 5 years before a tree is replanted, 0.82 metric tons of CO_2 per acre or around 1,000,000 kg of CO_2 per km^2 are removed by forestry. [6]

The following table shows the CO_2 released into the atmosphere per vehicle due to deforestation for each type of vehicle.

Table 3: Total carbon emissions due to deforestations

Vehicle Type	Total Deforestation (km^2)	CO2 Released (kg)
GV	$18.34*10^{-4}$	1,834
EV	$121*10^{-4}$	12,100
HEV	$82.5*10^{-4}$	8,250

Manufacturing

Once the raw materials are obtained, manufacturing is the second step in the process of creating (EVs) and (GVs). The most prominent effect on the carbon footprint of manufacturing is the energy requirement for the manufacturing process. An estimate on the energy consumption in MJ for (EVs) and (GVs) are approximately 95,000 MJ and 65,000 MJ respectively with coal, natural gas, and coke being used to create about 80% - 90% of the total energy requirement in both cases. Therefore, carbon emissions for (EVs) and (GVs) are 15,000 kg-CO_2 and 10,000 kg-CO_2 respectively as seen in Appendix 1. It can be noted in Appendix 2 that a small portion of the fuel in the (other) category contributes a comparable number of kg-CO_2 emissions as coal, natural gas, and coke combined; however, these fuels make up around 1% of the total energy requirements. This means that the energy sources have a significantly higher emission in kg-CO_2/MJ by a factor of at least 85 times that of coal, natural gas, and coke. If the fuel sources in the (other) category could be replaced, the total emissions due to manufacturing could be reduced by 40% or 4,500 kg-CO_2 and 3,000 kg-CO_2 for (EVs) and (GVs) respectively. [7]

In appendices 1 and 2, ICAE represents (GVs), and BEV represents (EVs). On a part-by-part basis, on a material-by-material basis, and on a fuel-by-fuel basis the energy consumption in (MJ) was almost directly proportional to the greenhouse gas emissions in kg-CO_2 eq excluding the (other) category in the fuel-by-fuel basis. [7]

Hyung Chul Kim, et. al. discusses the breakdown of production of (EV) battery packs. Over half of the material requirements of (EVs) comes from the battery pack, and over half of the mass of the battery pack comes from the Cell-Electrode/Collectors and Cell-Electrode/Separators. These two components make up around 25% of the total material mass requirement of the vehicle. When looking at the pollution emissions, around 85% of the total emissions come from the enclosure, cell manufacturing, and cell components. [8] Thus, the primary focus on reducing the pollution of (EVs) is to reduce the pollution emissions of these two components. In the discussion, the pollutant emissions due to manufacturing is compared to the pollutant emissions due to operation.

The amount of CO_2 released due to refining and production of aluminum and steel and the total CO_2 emissions are listed below in table 3.

Table 4: Total carbon emissions due to manufacturing [7]

Vehicle Type	Aluminum CO_2 Emissions (kg)	Steel CO_2 Emissions (kg)	CO_2 Released (kg)
GV	2,000	5,000	10,000
EV	3,000	7,000	15,000
HEV	3,000	7,000	15,000

Operation

Operation is the most studied stage of (EVs) and (GVs). This stage is the most important in determining the long-term effects of (EVs) and (GVs) on the global carbon footprint; however, this stage must mitigate the initial negative impact of carbon footprint from the mining and manufacturing stages. The primary difficulty with today's technology is that electrical energy is primarily produced using coal, oil, or natural gas which also has a carbon footprint. S.I. Ehrenberger, et. al. analyzes three different parallel hybrid vehicles (PHEVs) in four different driving modes. The specifications of the (PHEVs) are listed in the table 4 below. [9]

Table 5: Specifications for three different (HEVs) [7]

	PHEV 1	PHEV 2	PHEV 3
Type of hybrid	Parallel	Parallel	Parallel
Power of (ICE) [kW]	110	135	155
Power of electric engine [kW]	75	65	60
Overall system power [kW]	150	185	215
Battery Capacity [kWh]	8.7	7.6	6.4
Electric Range [km]	50	40	30
Electric energy consumption [kWh/100 km]	11.4	11.0	11.0
Fuel consumption [L/100 km]	1.5	1.9	2.1
CO_2 [g/km]	35	44	48
Emission standard	EURO 6b	EURO 6b	EURO 6b

The four different driving modes were Eco-Max Electric 100%

Charge, Comfort-Hybrid 100% Charge, Comfort-Hybrid 0% Charge, Sport Mode 0%. The results are presented in table 5 below. The tests were conducted on a single route that consisted of urban roads, rural roads, and motorways. When the (ICE) starts at high speeds due to acceleration requirements, NO_x emissions increase drastically due to the cold start of the catalytic converter which primarily occurred in the urban and rural sections of the test. Comparable results can be seen in particulate emissions. The Eco-Max and Comfort-Hybrid 100% charge cases for all (HEV) types saw only a slight increase in NO_x and particle emissions outside of the few cases of cold start. Oppositely, the Comfort-Hybrid and Sport-Hybrid 0%

charge cases for all (HEV) types saw a steady increase in NO_x and particle emissions throughout the test. CO_2 emissions seemed to steadily increase regardless of driving mode. The reason these spikes in emissions occur in the Eco-Max and Comfort-Hybrid 100% Charge is because these test modes primarily rely on the battery for power to run the drive train of the vehicle. Because the engine is not running the entire duration of the test drive, whenever the vehicle encounters high accelerations, the engine must start to adapt to the torque requirements. This repetitive cold-starting of the engine increases the NO_x and particulate matter emissions. [9]

Table 6: Emissions for three different (HEVs) for different driving modes. [7]

	Driving Mode	PHEV 1	PHEV 2	PHEV 3
CO2 (g/km)	Eco-Max 100% charge	60 + 10	100 + 10	120 ± 10
	Comfort-Hybrid 100% charge	110 + 10	100 + 10	120 ± 10
	Comfort-Hybrid 0% charge	120 + 10	120 + 10	160 ± 10
	Sport-Hybrid 0% charge	150 + 10	200 ± 10	280 ± 10
NOx (g/km)	Eco-Max 100% charge	0.012 + 0.002	0.014 ± 0.006	0.020 ± 0.020
	Comfort-Hybrid 100% charge	0.007 + 0.001	0.017 ± 0.002	0.025 ± 0.010
	Comfort-Hybrid 0% charge	0.012 ± 0.002	0.008 ± 0.001	0.035 ± 0.004
	Sport-Hybrid 0% charge	0.014 ± 0.004	0.033 ± 0.001	0.060 ± 0.002
Particulate (1E+12/km)	Eco-Max 100% charge	1.0 ± 0.3	1.4 ± 0.2	1.7 ± 0.3
	Comfort-Hybrid 100% charge	0.7 ± 0.1	1.1 ± 0.2	1.9 ± 0.2
	Comfort-Hybrid 0% charge	1.1 ± 0.3	0.8 ± 0.1	1.0 ± 0.2
	Sport-Hybrid 0% charge	1.4 ± 0.3	1.4 ± 0.2	0.7 ± 0.1

In terms of total CO_2, NO_x, and particulate matter, CO_2 and particulate matter emissions was consistent for all (HEV) types in all four cases; however, NO_x emissions are not consistent for the different test cases. The NOx emissions are almost double the amount in type 3 as in types 1 & 2. The type 3 (HEV) also saw a jump between the particulate emissions of the 100% charge modes and 0% charge modes. This jump, as discussed earlier, is caused by the cold-starts of the engine when primarily the battery is used in the Eco-Max and Comfort-Hybrid 100% modes. [9]

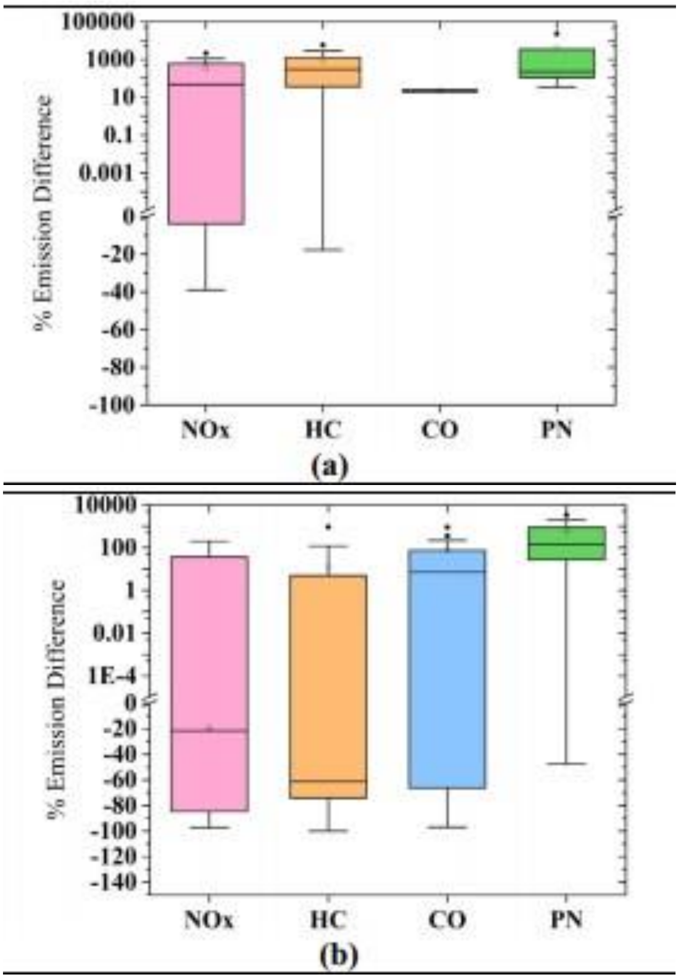

Figure 4: Percent difference in emissions of (HEVs) compared to (GVs). (a) Chassis dynamometer testing. (b) Road testing. [8]

Bagheri, et. al. discusses methods to improve the emissions of hybrid vehicles. Cold-starts occur because hybrid vehicles are usually designed to shut off the engine when the battery can be used to create enough torque. When the battery cannot produce enough torque, the engine starts up again; however, this start-up occurs under high torque requirements. Because the engine experiences high torque requirements when the engine is below normal operating temperature, thermal efficiency is significantly reduced resulting in higher emissions.

This result can be seen in figure 4. In the chassis dynamometer tests, the (HEV) emissions were 10-100 times higher than that of (GV) emissions on average. When a road test was completed, the NO_x emissions reduced by 20% and the HC emissions reduced by 60% in average. The CO and PN averages did not change; however, the spread of the data has reached into the negative percent. This means that some tests had worse emissions and some tests had better emissions for the road tests. This could likely be a result of cold-starting. Three methods to mitigate the effects of cold-starting are engine warm-up, engine calibration, and after-treatment. [10]

To achieve engine warm-up in a shorter time, electrical energy can be used to heat-up the catalyst. This results in higher catalyst conversion efficiencies and thus improved emissions. This strategy reduced HC and NO_x emissions by 40-50%. Similarly, starting the (ICE) during low load conditions while primarily using the battery reduced CO_2 emissions by 23% and reduced HC and NO_x emissions by 95%. [10]

According to Yang, et. al., when looking at the life cycle emissions of (EVs) compared to (GVs) in China, it becomes apparent that there is a slight reduction in CO_2 emissions and NO_x emissions due to reduction in fuel consumption; however, significant amounts of hazardous particulate matter are released due to the production of the lithium-ion battery and the production of electricity. The study looked at both purely electric and hybrid vehicles, and it was found that in some cases, use of a purely electric vehicle could increase the emissions of CO_2 by around 16-20%. The CO_2 emissions from production was sometimes greater than emissions from usage. Production emissions from electric vehicles were sometimes double that of gasoline vehicles. Despite this, on average, CO_2 emissions of (EVs) were lower than those of (GVs). [11]

According to the US EPA, electrical emissions are about 7.09×10^{-4} metric tons CO_2/kWh or 0.709 kg CO_2/kWh. [6]

Looking at the three (PHEVs) mentioned in S.I. Ehrenberger, et. al., the energy required to charge the battery in the 100% charge cases is shown in table 6 below.

Table 7: Emissions adjustment accounting for charging

Driving Mode		PHEV 1	PHEV 2	PHEV 3
Eco-Max 100% charge	Energy output from battery (MJ) [9]	50	40	30
	CO2 Emissions due to charging (kg)	9.85	7.88	5.91
	CO2 Emissions per mile (g/km) assuming 77 km trip	128	102	77
Comfort-Hybrid 100% charge	Energy output from battery (MJ) [9]	10	40	30
	CO2 Emissions due to charging (kg)	1.97	7.88	5.91
	CO2 Emissions per mile (g/km) assuming 77 km trip	26	102	77
Comfort-Hybrid 0% charge	Energy output from battery (MJ) [9]	0	-3	-4
	CO2 Emissions due to charging (kg)	0	-0.59	-0.79
	CO2 Emissions per km (g/km) assuming 77 km trip	0	-8	-10
Sport-Hybrid 0% charge	Energy output from battery (MJ) [9]	-9	-8	-10
	CO2 Emissions due to charging (kg)	-1.77	-1.58	-1.97
	CO2 Emissions per mile (g/km) assuming 77 km trip	-23	-21	-26

Adding these values to the CO2 emissions from the driving tests, the total emissions per km are obtained.

Table 8: Total emissions for three different (HEVs) for different driving modes. [7]

	Driving Mode	PHEV 1	PHEV 2	PHEV 3
CO2 (g/km)	Eco-Max 100% charge	188	202	197
	Comfort-Hybrid 100% charge	136	202	197
	Comfort-Hybrid 0% charge	120	112	150
	Sport-Hybrid 0% charge	127	179	254

From the table 7 above, it is clear that the average emissions of CO_2 per kilometer is less for the 0% charge cases than for the

100% charge cases; however, the average of the 12 cases (172 g/km) is still lower the average of gasoline vehicles (247 g/km) according to the US EPA [6]. Assuming a milage of 250,000 km for each vehicle, assuming 1 replacement of the lithium-ion battery, and considering around one-third of the copper is use for the lithium-ion battery, the following estimates are made for the carbon emissions during the operation phase.

Table 9: Maintenance related carbon emissions

Vehicle Type	Material	Weight (t)	Deforestation per material (km^2)
EV	Copper	10.7	38×10^{-4}
	Maintenance Emissions (kg)		3800
HEV	Copper	7.4	25.3×10^{-4}
	Maintenance Emissions (kg)		2530

Table 10: Total operation phase emissions

	GV	HEV
Road emissions (kg)	61,750	43,000
Maintenance emissions (kg)	0	2,530
Total emissions (kg)	61,750	45,530

When looking at the total CO_2, NO_x, and particulate matter compared to the Worldwide Harmonized Light Vehicles Test Cycle (WLTC) emission standards. For all types of (HEVs), the CO_2 emissions of the Road Tests were higher than the CO_2 emissions in the (WLTC) tests. The (WLTC) tests' CO_2 emissions were approximately the (WLTC) CO_2 emission standards, while the road test CO_2 emissions were significantly over the WLTC CO_2 emission standards. For all types of (HEVs), the NO_x emissions of the Road Tests were lower than the NO_x emissions in the (WLTC) tests. The (WLTC) tests' NO_x emissions were generally under the (WLTC) NO_x emission standards and the road test NO_x emissions were also significantly under the (WLTC) NO_x emission standards. For all types of (HEVs), the particulate emissions of the Road Tests were about the same as the particulate emissions as in the (WLTC) tests. The (WLTC) tests' particulate emissions and road test particulate emissions were around the (WLTC) particulate emission standards. [9]

Recycling Phase

The recycling phase is an important phase of the lifecycle of an automobile because in this phase, any salvageable material can be put to use in another automobile. This phase is particularly important in mitigating the mining and manufacturing phases. If most or all of the material and parts can be reused, the carbon emission reduction can almost cancel out the carbon emissions of mining and manufacturing. As discussed earlier in this paper, recycling could reduce the amount of energy required to refine aluminum and steel by 97% and 65% respectively. This also reduces the required mining by 97% and 65% for aluminum and steel, respectively.

Table 11: Total reduction in deforestation and related carbon emissions

Vehicle Type	Material	Weight reduction (t)	Deforestation reduction per material (km^2)
GV	Iron	-3.19	$-2.47*10^{-4}$
	Aluminum	-6.50	$-5.03*10^{-4}$
	Total deforestation reduction (km^2)		$-7.50*10^{-4}$
	Deforestation emission reduction (kg)		-750
EV	Iron	-3.71	$-2.87*10^{-4}$
	Aluminum	-3.10	$-2.40*10^{-4}$
	Total deforestation reduction (km^2)		$-5.27*10^{-4}$
	Deforestation emission reduction (kg)		-527
HEV	Iron	-3.64	$-2.82*10^{-4}$
	Aluminum	-2.81	$-2.17*10^{-4}$
	Total deforestation reduction (km^2)		$-4.99*10^{-4}$
	Deforestation emission reduction (kg)		-499

Table 12: Total reduction in manufacturing related carbon emissions

Vehicle Type	Material	Emission reduction(kg)
GV	Iron	-3250
	Aluminum	-1940
	Total manufacturing emission reduction	-5190
EV	Iron	-4550
	Aluminum	-2910
	Total manufacturing emission reduction	-7460
HEV	Iron	-4550
	Aluminum	-2910
	Total manufacturing emission reduction	-7460

Table 13: Total reduction in carbon emissions

	GV	HEV
Deforestation (kg)	-750	-499
Manufacturing (kg)	-5190	-7460
Total emissions (kg)	-5,940	-7,959

Health Effects

It is often difficult to quantify the health effects due to pollution emissions in the U.S. so two different methods will be focused upon. The two common methods to quantify health effects are cents per mile and micro deaths per ten thousand miles (deaths per 10 billion miles). The cents per mile and micro deaths per ten thousand miles benefit for transitioning from (GVs) to (EVs) ranges from 2 cents and 20 micro deaths respectively in Rochester, NY to 10 cents and 100 micro deaths respectively in New York, NY. Thus, there can be a significant variation in emission effects within a state or location. Around 60-80% of the cents and micro deaths benefits come from the reduction of NO_x and NH_3 and not from the reduction of carbon emissions. [12]

When considering the health effects of transitioning to (EVs), there is a cents per mile benefit ranging from 2-10 cents per mile for a total dollar amount of $3000-$15000 over the lifetime of the vehicle. Assuming there are 300 million Americans with a vehicle and that each American drives approximately 100 miles/day or around 36,500 miles per year, the total number of miles Americans would drive is 11 quadrillion miles per year. If the upper estimate of 100 micro deaths per ten thousand miles is used, an estimate of only 110 deaths per year or approximately two deaths every week in the United States. This number is exceedingly low when comparing to the total of 32,000 deaths per year due to car accidents. [13]

Comparing this overestimate of deaths per year in the United States according to the information obtained from Choma, et.al. to the estimated deaths of 4.2 million deaths per year globally obtained from the World Health Organization [14], it is seen that there is a significant discrepancy. There are two justifications for this discrepancy.

1. Automobile emissions have a negligible effect on the total deaths due to emissions.
2. Pollutant emissions in the United States are negligible compared to pollutant emissions in other countries.
3. Healthcare standards in the United States are significantly higher than other countries.

In any of these cases, focusing on the improvement of automobile emissions seems to have a negligible effect. The most likely scenario is that pollution emissions in countries such as China and India are having significant contributions to emission related deaths.

Summary

To analyze the pollution emission effect of transitioning from (GVs) to (EVs) the total emissions from each phase will be added. It is important to notice that the emissions from the recycling phase is negative because the total emissions are reduced by recycling.

Table 11: Total carbon emissions

Phase	Emissions (kg)	
	GV	HEV
Mining	1,834	8,250
Manufacturing	10,000	15,000
Operation	61,750	45,530
Recycling	-5,940	-7,959
Total	67,644	60,821

As shown in Table 11, (HEVs) have around 7000 kg less CO_2 emissions than (GVs) or around 10% less emissions. However,

in this analysis, there was limited data on deforestation found from literature and lithium and nickel were neglected. Lifetime of a vehicle in mileage can vary significantly as a result of factors such as car crashes and manufacturing defects.

Similarly, a well-kept vehicle could see significantly higher mileages than the expected average. Because of uncertainties in these variables, a perturbation analysis was done on the deforestation due to copper (α), the deforestation due to iron/aluminum (β), and the total milage of the vehicle (γ). These values were varied between 50% and 150% of their original values to determine how changes in the data could affect the overall conclusions. Lithium and nickel effects were combined with the copper deforestation.

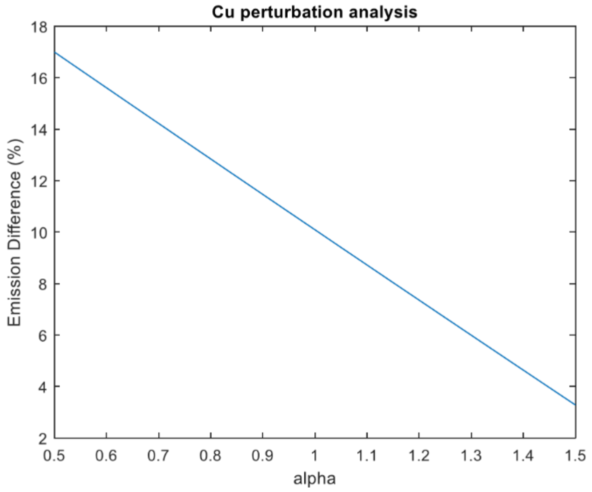

Figure 5: Cu perturbation analysis

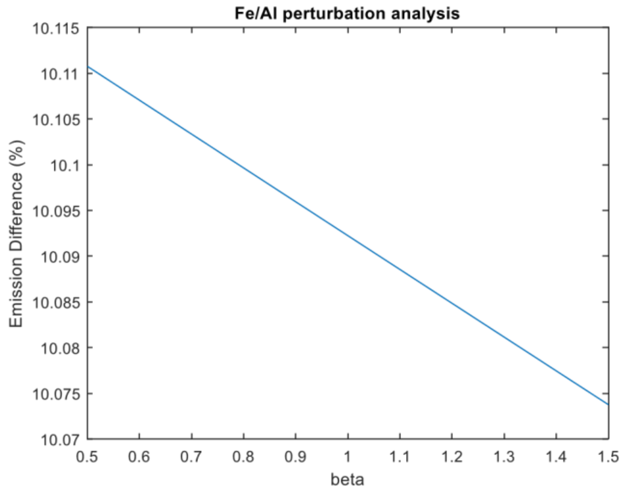

Figure 6: Fe/Al perturbation analysis

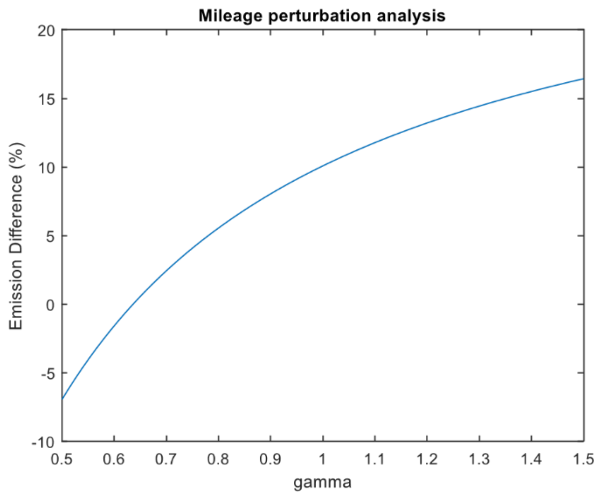

Figure 7: Mileage perturbation analysis

As seen from figures 5, even with a significant increase in copper deforestation combined with a likely overestimation of copper related deforestation, the emission difference is still above 3%. This means that perturbation of copper deforestation alone cannot affect the overall conclusion.

As seen from figures 6, perturbation of iron/aluminum related deforestation has a negligible affect on the results. This is due to the assumption of 65% and 97% recycling of iron and aluminum, respectively. As seen in Appendix 8 & 10, even when combined with perturbations of the two other variables, iron/aluminum related deforestation has a negligible affect on the emission difference.

Figure 7 on the other hand, shows a significant affect from the variation of the average mileage of the vehicle. At a 30% reduction in mileage, the emission difference becomes almost zero. Meaning that an electric vehicle needs to be driven at least 175,000 km to become beneficial for the environment. When combined with the maximum perturbation of deforestation due to copper, electric vehicles need to be driven 200,000 km to 225,000 km at a minimum to be beneficial.

Appendix tables 3-7 show the combined affects of varying all three variables. Again, it can be seen that iron/aluminum affects are negligible; however, variations in copper deforestation and mileage contribute to a range in the emission difference from -20% to 20%. To eliminate any uncertainty in the results, future studies should focus on improving the accuracy of the copper related deforestation and on investigating the total average mileage of the vehicle.

Lastly, considering the health effects of transitioning to electric vehicles, it was found that deaths due to pollutant emissions were around 1% of those due to car accident related deaths meaning that the operation stage was the deadliest stage of the lifecycle of a car but for different reasons than expected.

When compared to WHIO statistics, there was an astonishing discrepancy in the total deaths per year. From this data, it was concluded that emissions in the United States were negligible compared to emissions in counties such as China and India.

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Definitions/Abbreviations

EV	electric vehicle
GV	gasoline vehicle
HEV	hybrid electric vehicle
PHEV	plug-in hybrid electric vehicle
ICE	Internal Combustion Engine
TMR	Total Material Requirement
WLTC	Worldwide Harmonized Light Vehicles Test Cycle
HC	Hydrocarbon
PN	Particle Number
Cu	Copper
Ni	Nickel
Li	Lithium
Al	Aluminum
Fe	Iron
GHG	Green House Gas
US EPA	United States Environmental Protection Agency
WHO	World Health Organization
CDC	United States Center for Disease Prevention and Control

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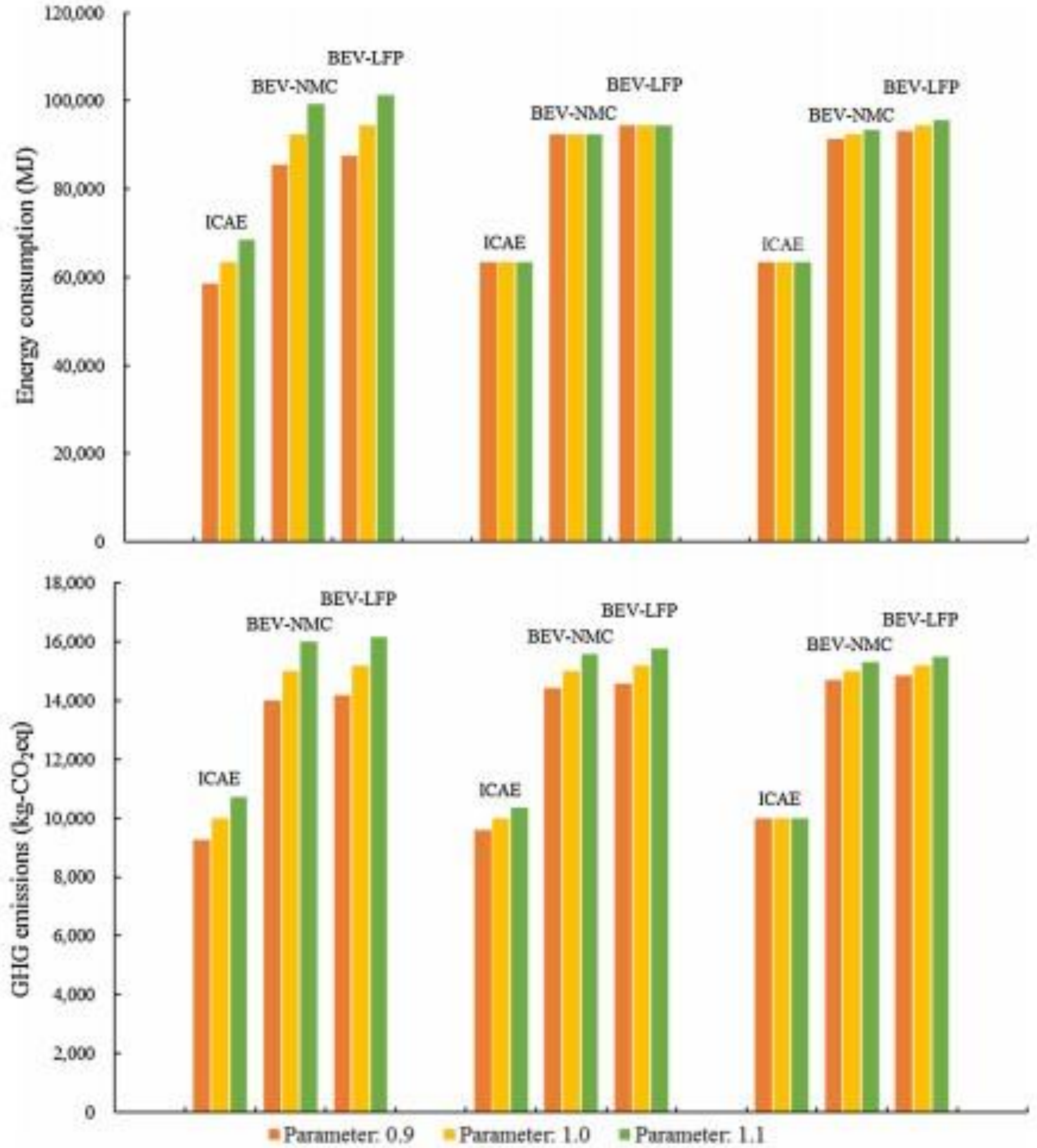
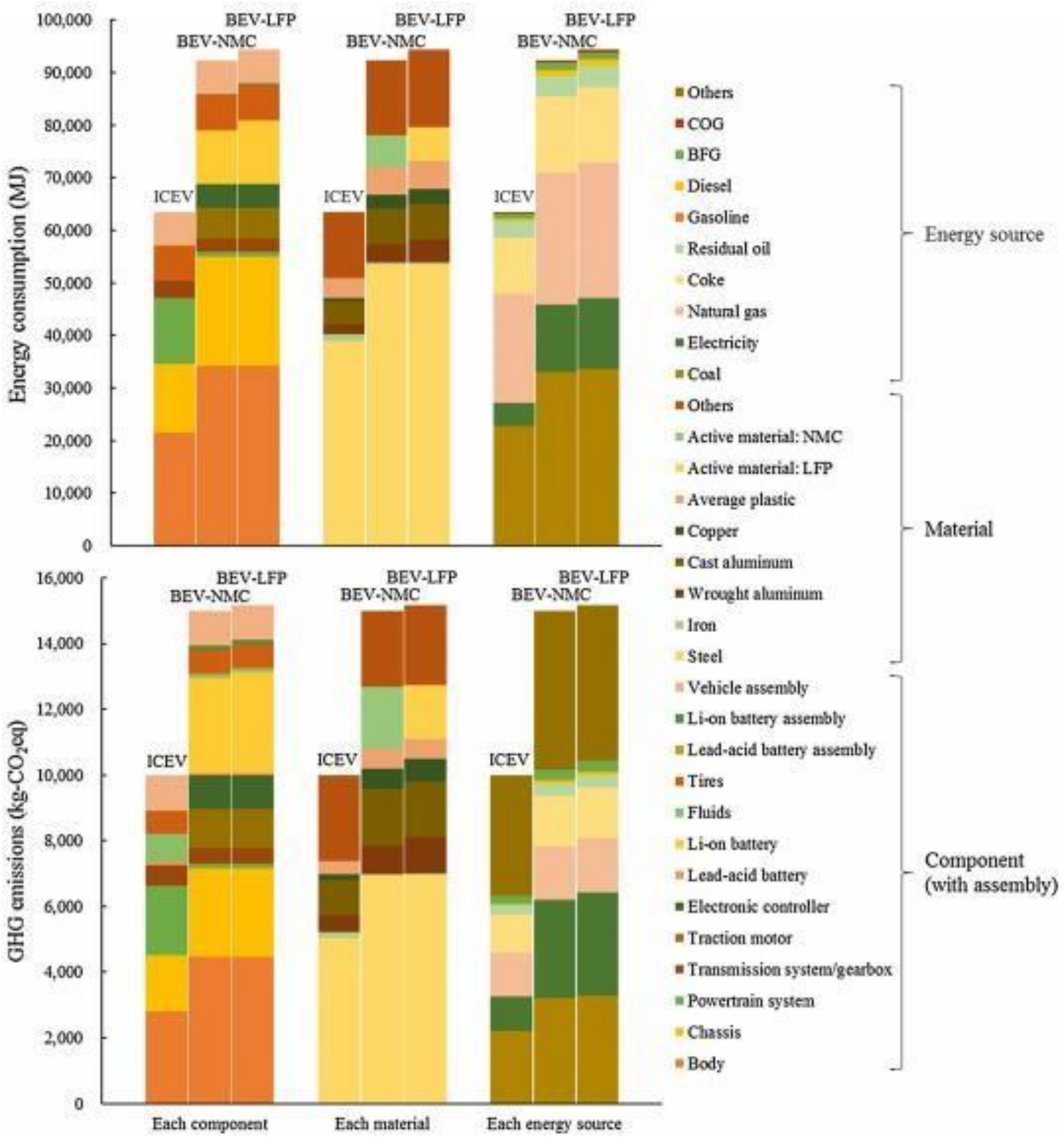
Appendix



Appendix 1: Energy consumption and GHG emissions when (a) curb weight, (b) GHG emission factor of electricity production, (c) energy consumption and GHG emissions of Li-ion battery production are multiplied by sensitivity parameters. [7]



Appendix 2: Total energy consumption and GHG emissions. [7]

Appendix 3: Emission difference in (%) compared to GVs, γ = 0.5

	α = 0.5	α = 0.75	α = 1	α = 1.25	α = 1.5
β = 0.5	5.65	-0.68	-6.93	-13.10	-19.20
β = 0.75	5.64	-0.68	-6.93	-13.10	-19.18
β = 1	5.63	-0.69	-6.93	-13.09	-19.17
β = 1.25	5.62	-0.70	-6.93	-13.08	-19.16
β = 1.5	5.60	-0.70	-6.93	-13.08	-19.15

Appendix 4: Emission difference in (%) compared to GVs, γ = 0.75

	α = 0.5	α = 0.75	α = 1	α = 1.25	α = 1.5
β = 0.5	13.04	8.56	4.11	-0.29	-4.65
β = 0.75	13.02	8.54	4.11	-0.29	-4.65
β = 1	13.01	8.53	4.10	-0.30	-4.66
β = 1.25	13.00	8.52	4.09	-0.30	-4.66
β = 1.5	12.98	8.51	4.08	-0.31	-4.66

Appendix 5: Emission difference in (%) compared to GVs, γ = 1

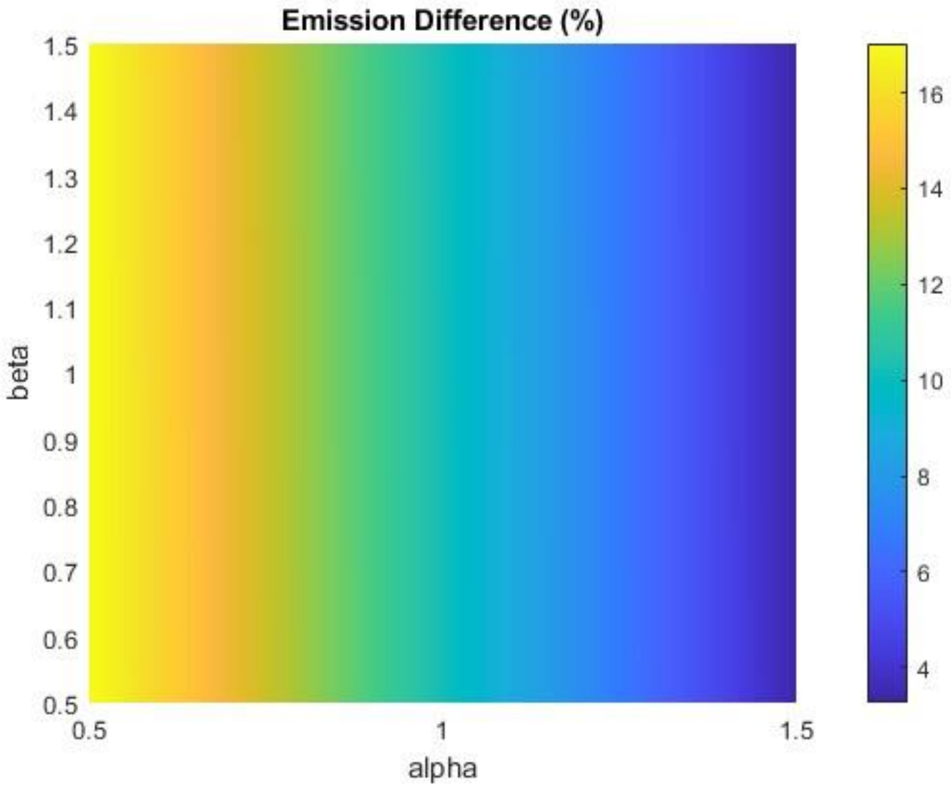
	α = 0.5	α = 0.75	α = 1	α = 1.25	α = 1.5
β = 0.5	17.02	13.56	10.11	6.69	3.29
β = 0.75	17.01	13.54	10.10	6.68	3.29
β = 1	17.00	13.53	10.09	6.68	3.28
β = 1.25	16.98	13.52	10.08	6.67	3.28
β = 1.5	16.97	13.51	10.07	6.66	3.27

Appendix 6: Emission difference in (%) compared to GVs, γ = 1.25

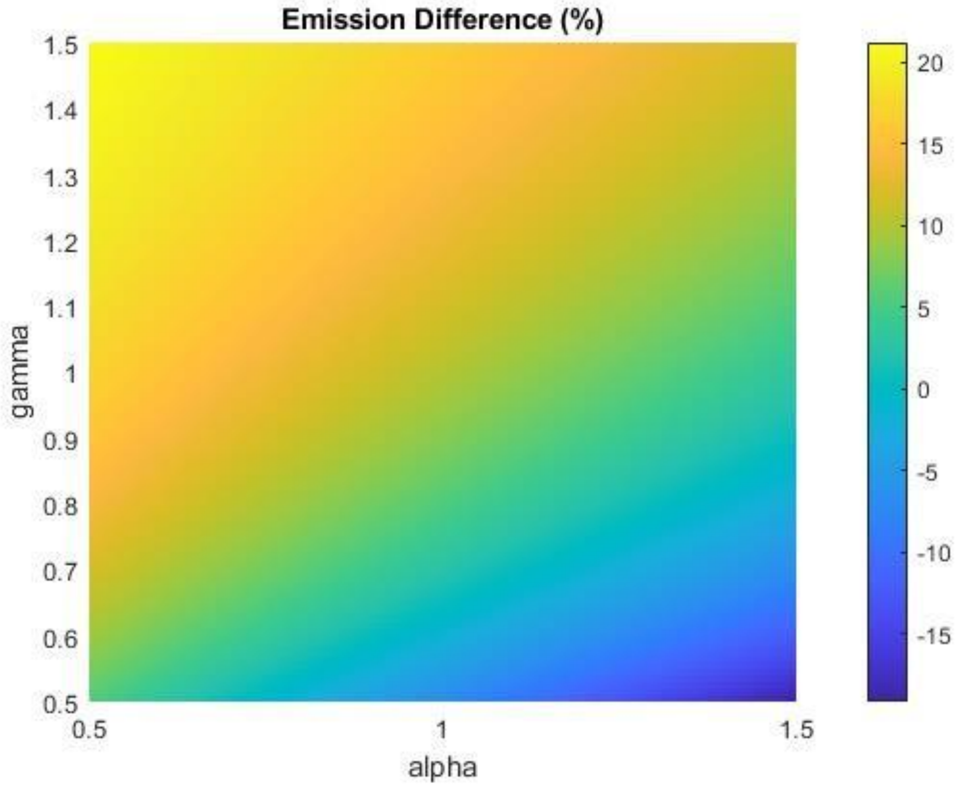
	α = 0.5	α = 0.75	α = 1	α = 1.25	α = 1.5
β = 0.5	19.52	16.69	13.88	11.08	8.30
β = 0.75	19.51	16.68	13.87	11.07	8.29
β = 1	19.50	16.67	13.86	11.06	8.29
β = 1.25	19.48	16.66	13.85	11.06	8.28
β = 1.5	19.47	16.65	13.84	11.05	8.27

Appendix 7: Emission difference in (%) compared to GVs, γ = 1.5

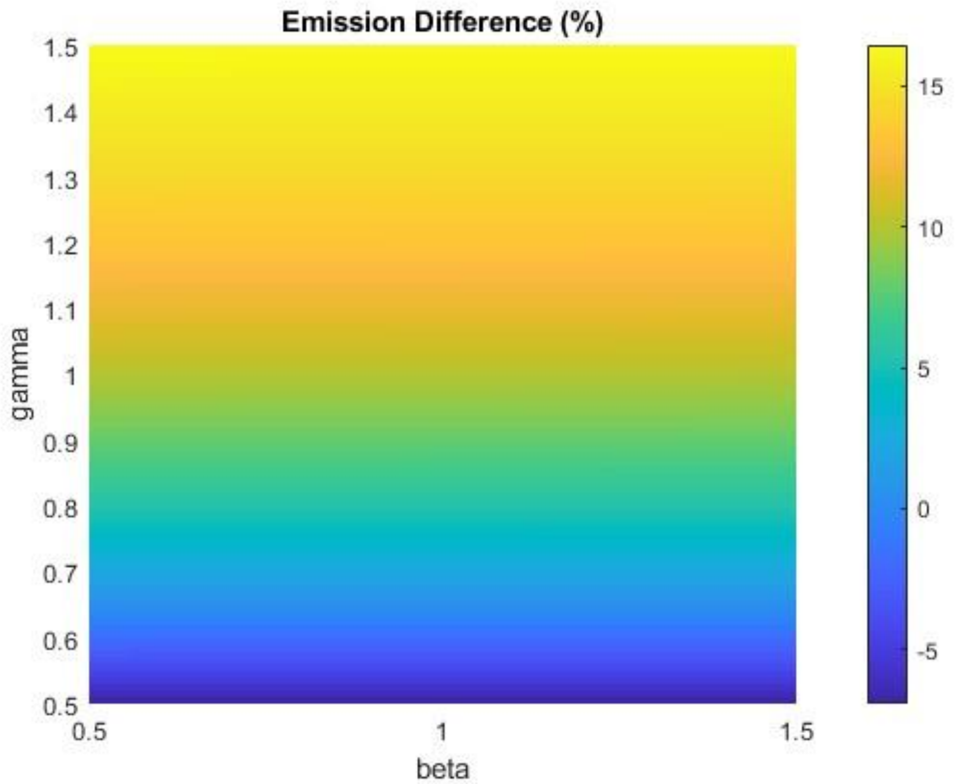
	α = 0.5	α = 0.75	α = 1	α = 1.25	α = 1.5
β = 0.5	21.23	18.84	16.46	14.10	11.74
β = 0.75	21.22	18.83	16.45	14.09	11.74
β = 1	21.21	18.82	16.45	14.08	11.73
β = 1.25	21.20	18.81	16.44	14.07	11.72
β = 1.5	21.19	18.80	16.43	14.07	11.72



Appendix 8: Cu and Fe/Al perturbation analysis



Appendix 9: Cu and Mileage perturbation analysis



Appendix 10: Fe/Al and Mileage perturbation analysis