

The Predicted Relationship Between Relating Factors on Electric Vehicles and Carbon Dioxide Emissions in the United States

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ABSTRACT

In recent years, vehicle electrification is promoted around the world to reduce greenhouse gas emissions. As electric vehicles (HEV, PHEV, BEV) are taking a bigger portion of the market share every year, it is important to find out whether this trend does provide environmental benefits in real life. Many previous studies have investigated the topic regarding electric vehicles and emissions: a lot of comparisons between the lifecycle emissions of electric vehicles and internal combustion engine vehicles are done by scholars around the world, most indicating that EVs produce less lifecycle emission than ICEVs. While most of these studies are done from a microscopic perspective by taking very detailed regional data, this study is trying to develop a prediction for the relationship between the sales of electric vehicles and carbon dioxide emissions from a broader perspective. The scope of this study is from 2000 to 2018 in the United States and the data is taken from the U.S. Energy Information Administration and Bureau of Transportation Statistics, U.S. Department of Transportation. A multiple linear regression model is developed where the independent variables include the sales number of EVs and variables related to the lifecycle of EVs: electricity production, petrol price, industrial sector energy consumption, transportation sector energy consumption and the sales of ICEVs; the dependent variable is carbon dioxide emission. After establishing a linear model for these variables in RStudio, a negatively proportional relationship between the sales number of EVs and carbon dioxide emission is discovered (coefficient = -1.769×10^{-3} , p-value = 1.29×10^{-5}). Besides that, petrol price and transportation sector energy consumption are also factors that have a significant effect (at $\alpha = 5\%$) on the dependent variable. Although the data for some variables might not be precise enough, the regression model proves that the rising sales of EVs correspond with the reduction of carbon dioxide emission.

Keywords: *Electric vehicle, Carbon dioxide emissions, Multiple linear regression*

1. INTRODUCTION

Global warming is one of the most serious environmental issues faced by mankind. Technological advancement comes with its byproduct — an increasing amount of greenhouse gases (GHG) released into the atmosphere for centuries, trapping more heat that causes the global temperature to rise. Among all the greenhouse gases produced by us, carbon dioxide takes the largest proportion, 65% in 2010 [22]. In the United States, GHG emissions are produced by different economic sectors: the electric power sector, industrial sector, transportation sector, residential sector and commercial sector.

On the other hand, the motoring industry is influenced significantly by the combined forces of global warming and the depletion of fossil fuels in recent years. All around the world, government regulations force car manufacturers to gradually reduce their reliance on internal combustion engines and shift their attention elsewhere. Due to these reasons, electric vehicles (EV) such as battery electric vehicles (BEV), hybrid-electric vehicles (HEV) and plug-in hybrid-electric vehicles (PHEV) (the difference between them will be explained in the Literature Research section) are replacing internal combustion engine vehicles (ICEV). As this trend catches on, it keeps people wondering: Do these electric or hybrid vehicles help reduce carbon dioxide emissions?

Indeed, EVs are entirely or partly powered by electric motors which produce less tailpipe carbon emissions. However, they put more pressure on power plants since more electricity has to be produced to power these motors. In order to generate more electricity to power EVs, the electric power sector might produce more emissions. Moreover, the production process of lithium-ion batteries that are used to power EVs sometimes generates even more carbon dioxide emissions than those generated in the electric power sector [11]. When all these extra emissions add up, it is hard to tell whether EVs or ICEVs produce more emissions in their lifecycles. As more and more EVs appear on the streets, it is more urgent than ever to figure out whether the development of the motoring industry is really on the right track: reducing carbon dioxide emission for the entire society.

Around the world, scholars have done some valuable researches on topics relating to EVs and carbon dioxide emissions. Many studies are conducted practically by analyzing public data and surveys. Comparisons about carbon dioxide emissions of electric vehicles and internal combustion vehicles are done by Berger and Jorgensen [5] to realize the potential for electric vehicles to reduce carbon dioxide emissions. German researchers look at the activities of commercial transport in different economic sectors and discuss the potential of reducing emissions by replacing them with EVs [13]. From a theoretical perspective, researchers utilize various models to predict the carbon dioxide emission of electric or hybrid vehicles. Some scholars in Italy create a deep neural network-based model to predict the carbon dioxide emission of hybrid electric vehicles [16]. A scholar in Finland uses simulations to predict carbon dioxide emission of EVs under cold temperatures [14]. On the subject of electric vehicles and carbon dioxide emissions, most scholars take on a small perspective. They directly investigate or create models to predict the carbon dioxide emissions of EVs in specified circumstances. When they include all the variables using data collected from experiments or local authorities, they can deduce the causality between variables. Due to the limitation of data, I have to investigate the two variables in the big picture. Around the lifecycle of electric vehicles, I listed several variables other than the sales of EVs to produce a prediction between them and carbon dioxide emission using multiple linear regression. The scope of my investigation will be in the United States from 2000 to 2018. My research question is: What is the potential influence of the sales number of electric vehicles and its relating factors on carbon dioxide emissions in the United States?

The importance of this investigation is that it examines the general trend between carbon emission and sales of electric and hybrid vehicles in a statistical perspective, which is rarely done by other scholars before. Using multiple linear regression model, we can deduce whether there exists a significantly negative relationship between the two variables, and factors that contribute to

it if there is. Supplementing results produced in other researches, this investigation provides more evidence for future researches on the same topic and insights into the potential environmental benefits of electric cars for the general public.

2. LITERATURE REVIEW

2.1. HEV, PHEV and BEV

The three main components of modern days electric vehicle market are hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV) and battery electric vehicles (BEV). Although they are all propelled by electric motors, HEV, PHEV and BEV have different running mechanisms.

A hybrid electric vehicle is powered by a combination of an internal combustion engine (ICE) and one or several electric motors. Although batteries can power electric motors, they cannot be charged directly from plugs. Instead, HEVs charge their batteries using regenerative braking to convert kinetic energy into electricity. Besides that, ICEs are used to recharge the batteries or power the electric motor directly. These technologies enable HEVs to achieve better fuel economy and produce fewer emissions than their ICE counterparts [2]. HEVs can be mild hybrids or full hybrids. Mild hybrids use electric motors to assist ICEs, mainly during stop-and-go traffic so that ICEs can be shut down and reduce idle emission. Mild hybrids cannot travel on the electric motor alone whereas full hybrids can. Their more powerful electric motor and larger battery enables full hybrids to travel short distances thus achieving better fuel economy [3].

A plug-in hybrid electric vehicle also has an ICE and an electric motor. Different from an HEV, the batteries of a PHEV can be charged externally by a plug, by the ICE or by the regenerative braking system. With larger batteries than most HEVs, PHEVs can run on pure electricity and without the ICE for some distance (15 to 60-plus miles in current models). ICE and electric motor cooperate in two different ways: A light-duty PHEV may use the electric motor most of the time and the ICE only assists during rapid accelerations and times of heavy electric burden or when the batteries run out. On the contrary, a heavy-duty PHEV may use the ICE most of the time and use the electric motor to power the gadgets. Thanks to its pure-electric drive system, PHEVs can achieve zero tailpipe emissions during short journeys such as commutes and great fuel economy. PHEVs have parallel and series configurations: Both the ICE and the electric motor can drive the wheels in parallel mode, whereas ICE is only used to generate electricity in series mode [4].

A battery-electric vehicle is powered by its electric motor. Like a PHEV, a BEV also has a chargeable battery pack. Current BEVs generally have a shorter range and

are more expensive than ICEVs, but their own can benefit from fuel savings and subsidies since the U.S. EPA categorizes BEVs as zero-emission vehicles (ZEV) [1].

In recent years, the number of electric vehicles (combination of HEV, PHEV and BEV) are rising significantly in the United States. The number of EVs rises from about 566 thousand (taking 3.28% of the market share) in 2017 [15] to more than 1.8 million in 2020 [8]. Among the three categories of EVs we discussed earlier, the number of BEVs grows at the fastest rate, from fewer than 300 thousand in 2016 to more than 1.1 million in 2020. In 2020, U.S. represents about 17% of the world's EV market, less than China (44%) and Europe (31%).

2.2. Lifecycle emission of electric vehicle

One of the main reasons why electric vehicles are promoted around the world is that EVs have the potential to reduce greenhouse gas emissions. Since EVs are less reliant on internal combustion engines than ICEV, they generally also produce fewer tailpipe emissions. However, the process of battery manufacturing and electricity production contributes greatly to the lifecycle emissions of EVs, adding uncertainty to whether or not EVs are environmentally friendlier than ICEVs. Studies are done to investigate the lifecycle emissions of EVs under different circumstances, make comparisons between the lifecycle emissions of EVs and ICEVs and estimate the potential GHG reduction.

Most studies have shown that EVs produce less GHG emissions in their lifecycles than ICEVs do:

Researchers at the University of Toronto estimate the GHG emissions of EVs in Great Toronto and Hamilton Area in Ontario, Canada. In the process of estimating EV lifecycle emissions, they use multiple linear regression and historical electricity generation data to find the marginal emission factor (MEF) and develop five charging scenarios at 5% and 30% EV penetration rate. By comparing EV and ICEV lifecycle emissions (obtained through a simulator), they conclude that vehicle electrification can drastically reduce GHG emissions, saving more than 75% GHG fuel cycle emissions with the 2017 electricity generation mix. They also find out that night charging can result in a large proportion of emission reduction [10].

A study in Norway has done a lifecycle GHG emissions assessment of electric vehicles in various sizes and ranges. Researchers collect curb weight and NEDC energy requirements for EVs, and break down their lifecycle to assess emissions in each phase. First of all, they discover that smaller and more energy-efficient EVs have lower lifecycle emissions than larger ones do. Through the comparison of EV and ICEVs, they find that EVs are more environmentally intensive in the production phase, but have lower user phase emissions.

In general, EVs have 20% ~ 27% lower lifecycle emissions than ICEVs do at the same size [9].

A study held in the United States incorporates marginal grid mixes to calculate GHG emissions from EVs and ICEVs more accurately. They separate the country by 13 NERC electricity generation regions and calculate their marginal grid mix, GHG emission and oil consumption respectively. They discover that ICEVs have the highest average marginal GHG. If HEVs are replaced with BEVs, GHG emissions would increase 7% averaged over the country. In most of the regions, PHEVs have high GHG emissions than HEVs. However, comparing with HEVs, BEVs would reduce oil consumption by 92%, whereas PHEVs would only reduce it by 36% [19].

Despite the differences in methodology, scope and time, most of the studies come up with the conclusion that EVs produce less lifecycle GHG emissions than ICEVs. The extent to which GHG emissions are reduced by vehicle electrification is not consistent due to a variety of reasons, but the general direction is clear.

One of the most important purposes of electric vehicles is to help reduce greenhouse gas emissions. As indicated by many studies, vehicle electrification seems to have this effect from a micro perspective. The aim of this investigation, however, is to find out whether this trend persists in a broader range. Therefore, a multiple linear regression analysis is done. The dependent variable is carbon dioxide emissions (CO₂). The independent variables are the sales of EVs (EV) and several factors related to the lifecycle of EVs. The data that will be examined from the United States of America from 2000 to 2018. My argument is that carbon dioxide emissions will be negatively proportional to the sales of electric vehicles in the United States.

3. METHODOLOGY

3.1. Variable justification

The main goal of this study is to investigate the relationship between carbon dioxide emissions and electric vehicles sales in the U.S. To break down this analysis into a more detailed perspective, independent variables related to the subject is also included: electricity production (EP), industrial sector energy production (ISC), transportation sector energy consumption (TSC), petrol price (PP), and the sales of internal combustion engine vehicles (ICEV). These variables are also assessed by other researchers during related studies.

Electricity production describes the total net generated electricity in the U.S. As the number of EVs increases, more electricity is generated to sustain the using phase and production phase of EVs. In this case, it is very likely that carbon dioxide emissions increase as well since more fuel has to be burnt to generate extra

electricity. This trend is shown by a study in Europe [17].

H1 (Hypothesis for electricity production):

Electricity production is positively proportional to carbon dioxide emissions.

The industrial sector is an important part both for the lifecycle of EVs and also the total carbon dioxide emission. In 2020, the industrial sector has the highest energy consumption among all the economic sectors [21]. Industrial sector emissions also take up a big part of EVs’ lifecycle GHG emissions since the production of lithium-ion batteries is very carbon-intensive. When more energy is consumed to produce EVs, carbon emission is likely to increase as well. However, this relationship is not likely to be strong, as a study has shown that the GHG emissions reduction caused by using the repurposed batteries in the industrial sector is far less than that in the residential sector [18].

H2 (Hypothesis for industrial sector energy consumption):

Industrial sector energy consumption is positively proportional to carbon dioxide emissions.

As the trend of vehicle electrification catches on, more and more vehicles run on electricity instead of petrol. Since EVs produce little tailpipe emissions, their impact on the environment cannot be comprehensively demonstrated through transportation sector emissions. Instead, the total energy consumption of the transportation sector includes the energy consumption of all power sources which is a better indicator of GHG emissions. When more energy is consumed, there should

also be more GHG emissions.

H3 (Hypothesis for transportation sector energy consumption):

Transportation sector energy consumption is positively proportional to carbon dioxide emissions.

Petrol price is another important variable relating to EV sales and carbon emission. Petrol is the energy source for ICEVs, and it is a substitute for electricity. As more and more people drive EVs instead of ICEVs, demand for petrol and its price might be negatively affected [12]. When less petrol is consumed, the carbon emissions in the transportation sector are likely to decrease. To specify petrol price into the petrol used by ICEVs, the category used in this investigation takes the “refiner price of finished motor gasoline to end-users”. The petrol price for each year takes the average petrol price for each month in a year.

H4 (Hypothesis for petrol price):

Petrol price is positively proportional to carbon dioxide emissions.

At last, the sales number of internal combustion vehicles is also a variable worth including. Taking up most of the market share in the motor industry, ICEV is not only a substitute for EV, but also a main contributor to transportation sector emissions.

H5 (Hypothesis for internal combustion vehicles):

The sales number of internal combustion vehicles is positively proportional to carbon dioxide emissions.

Table 1. Research variables

Variable name	Symbol	Unit	Source
Carbon dioxide emission	CO2	Million metric tons	EIA
EV sales	EV	/	U.S. department of transportation
Electricity production	EP	Billion kilowatthours	EIA
Industrial sector energy consumption	ISC	Trillion Btu	EIA
Transportation sector energy consumption	TSC	Trillion Btu	EIA
Petrol price	PP	dollar	EIA
ICEV sales	ICEV	/	U.S. department of transportation

3.2. Data collection

All of the data used in this investigation is obtained from public databases. The sales of EVs and ICEVs are developed by the Bureau of Transportation Statistics, United States Department of Transportation. The sales

number of EVs is obtained from a dataset titled “Hybrid-Electric, Plug-in Hybrid-Electric and Electric Vehicle Sales” [7]. It shows the sales of HEV, PHEV and BEV from 2000 to 2020. The sales number of ICEVs is obtained from a dataset titled” Annual U.S. Motor Vehicle Production and Domestic Sales” [6]. The data that I used is total domestic sales (since total production

doesn't include import and export) from 2000 to 2018.

The data for all the other variables are obtained from the United States Energy Information Administration [20]. Data for carbon dioxide emission is found at the EIA website titled "Energy-Related CO2 Emission Data Tables" in dataset "Table 2. State energy-related carbon dioxide emissions by year, adjusted". Data for electricity production, industrial sector energy consumption and transportation sector energy consumption is found on the EIA website titled "Monthly Energy Review". Data for EP is found under the "Electricity" section, "7.1 Overview". Data for ISC and TSC is found separately under the "Energy consumption by sector" section in "2.4 Industrial sector energy consumption" and "2.5 Transportation sector energy consumption".

The tool for data analysis used in this study is RStudio. All of the data are recorded in xls or xlsx files, which are imported from the "readxl" package from RStudio. After data clearing, all of the data is stored in a data frame with variable names as the column names and years as row names. At last, a multiple linear regression model is developed through the "lm" function.

3.3. Method justification

In this study, multiple linear regression is used to predict the relationship between carbon dioxide emission and variables related to the sales number of EVs. "Multiple linear regression generalizes the simple linear regression model by allowing many regressors in a mean function" [23]. Since there are many factors affecting carbon dioxide emissions, the sales number of EVs can only count for a tiny portion of the total influence. Adding more factors related to the topic can reduce the amount of uncertainty by presenting explanations from different perspectives. Using all of the variables in table 1, I established the following equation:

$$CO2_i = \beta_0 + \beta_1EV + \beta_2EP + \beta_3PP + \beta_4ISC + \beta_5TSC + \beta_6ICEV + \epsilon \tag{1}$$

In this equation, β_0 is the constant term as well as the y-intercept of the line. β_1 to β_6 are the coefficients of the independent variables. ϵ is the error term. Ordinary least square estimation is used to establish a model that has the smallest error for all the variables

Table2. Prediction of carbon dioxide emission versus variables related to EV

Variable	Coefficient	Standard error	t-value	p-value
EV	-1.769×10^{-3}	2.499×10^{-4}	-7.078	$1.29 \times 10^{-5*}$
EP	-7.441×10^{-2}	8.013×10^{-1}	-0.093	0.9275
PP	2.501×10^2	1.011×10^2	2.473	0.0293*
ISC	3.212×10^{-2}	7.398×10^{-2}	0.434	0.6718
TSC	1.784×10^{-1}	7.238×10^{-2}	2.465	0.0298*
ICEV	1.523×10^{-5}	3.828×10^{-5}	0.398	0.6978
Multiple R squared: 0.8918				
Adjusted R squared: 0.8377				
F-statistic: 16.48				
p-value: 3.701×10^{-5}				

4. RESULT

After importing all the data into RStudio, the predicted results for the multiple linear regression model are calculated and shown in Table2.

According to the analysis, the R^2 of the model is 0.8918, the F-statistic is 16.48 and the p-value is 3.701×10^{-5} . Since the p-values of electricity production, industrial sector energy consumption and the sales number of internal combustion engine vehicles are higher than 0.05, the null hypothesis cannot be rejected. Therefore, I can conclude that at 5% significant level, these variables don't have a significant effect on carbon dioxide emission.

At the same time, there are also three variables that have a lower p-value than 0.05: sales number of EVs, petrol price and transportation sector energy consumption. These variables have a significant effect on carbon dioxide emission. Since the data from 2000 to 2018 is taking into account, the Degrees of Freedom(df) equals to:

$$df = n - 1 = 19 - 1 = 18 \tag{2}$$

At these Degrees of Freedom, the absolute value of critical t-value is 2.101.

4.1. Sales number of EV

In this model, the sales number of electric vehicles has a significantly negative relationship with total carbon dioxide emission in the United States. It has a coefficient of -1.769×10^{-3} and the t-value is significant at $\alpha =$

5%. In figure 1, we can see that the sales number of EVs have a negatively proportional relationship with carbon dioxide emission in the U.S. so the argument proposed in part 2 is satisfied. This means, on a macro perspective, the rise of EV sales does correspond with decreasing carbon dioxide emissions in real life.

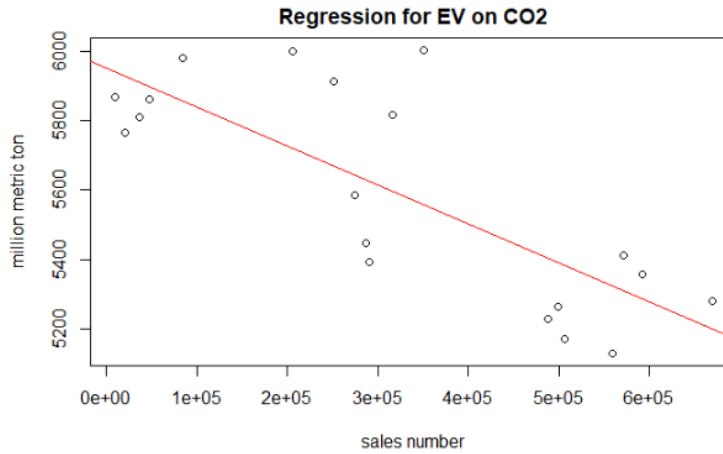


Figure 1 EV sale number verses CO₂ emission

4.2. Electricity production

Meanwhile, electricity production has a negative but insignificant relationship with carbon dioxide emission. It has a coefficient of -7.441×10^{-2} but the t-value is not significant at $\alpha = 5\%$. In figure 2, we can see that

although there appears to be a negative linear relationship, a sum of errors is quite large since many points are far from the line. Moreover, the result for electricity production contrasts with the study mentioned in the methodology part since a negative relationship is discovered instead of a positive one. Therefore, H1 can be refuted.

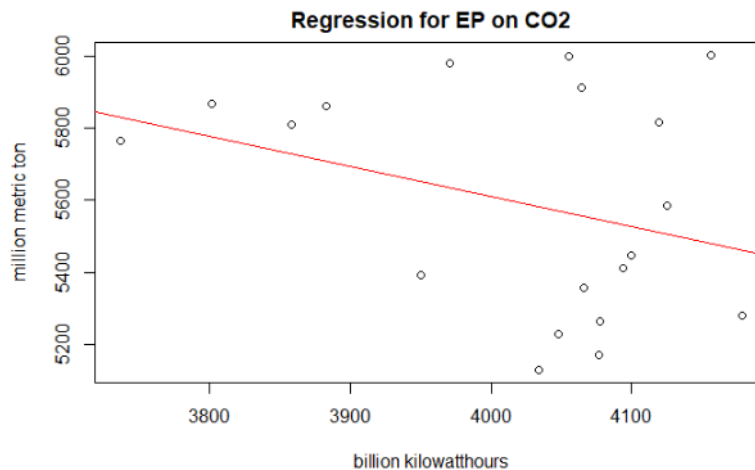


Figure 2 electricity production versus CO2 emission

4.3. Industrial sector energy consumption

Industrial sector energy consumption has a positive but insignificant relationship with carbon dioxide emission in the model. Its coefficient is 3.212×10^{-2} but its t-value is insignificant at $\alpha = 5\%$. In figure 4,

sample dots are scattered dispersively and far away from the line, which means that the linear relationship between ISC and CO₂ alone is weak. Although the positive relationship between ISC and CO₂ is in line with the proposal in H2, the t-value shows that ISC has a very weak influence on CO₂ in the multiple linear regression model.

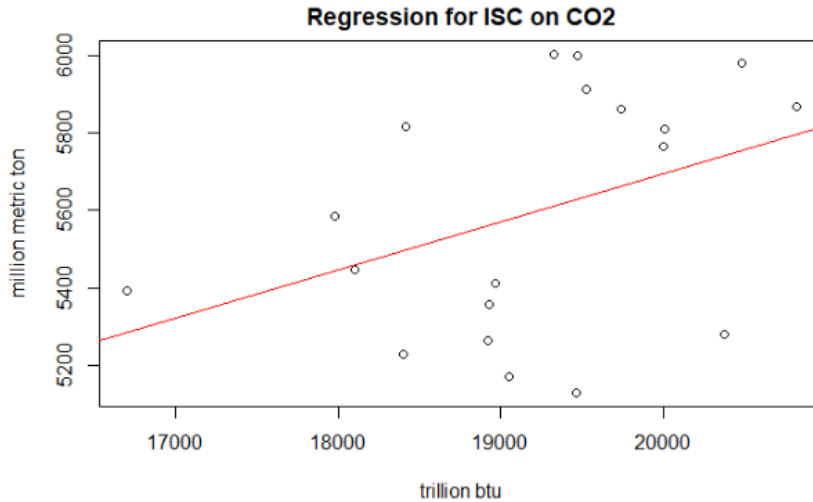


Figure 3 industrial sector energy consumption versus CO2 emission

4.4. Transportation sector energy consumption

Transportation sector energy consumption has a significantly positive relationship with carbon dioxide emission. It has a coefficient of 1.784×10^{-1} and its t-

value is significant at $\alpha = 5\%$. In figure 5, we can see that the direct effect of TSC on CO2 is weak, since the samples are neither precise nor accurate comparing to the line. However, the general trend is positive and TSC is significantly affecting CO2 in the multiple linear regression model, so H3 is satisfied.

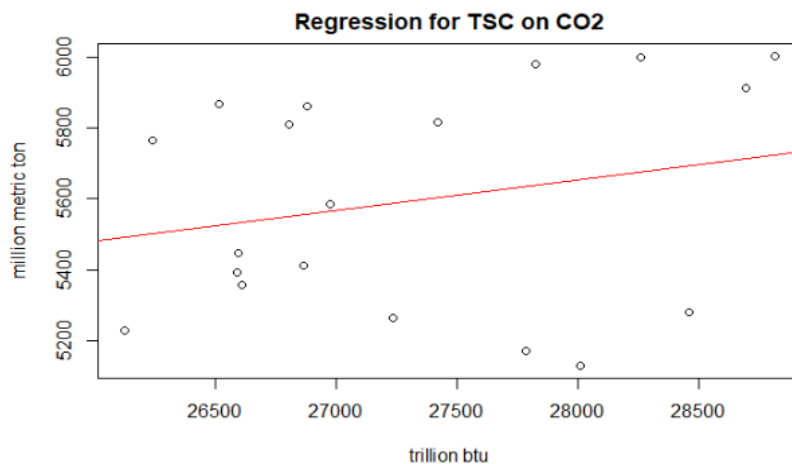


Figure 4 transportation sector energy consumption versus CO2 emission

4.5. Petrol price

According to the linear model, petrol price has a positive and significant relationship with carbon dioxide emission. It has a coefficient of 2.501×10^2 and the t-value is significant at $\alpha = 5\%$. In the model of six variables, petrol price is positively proportional to carbon dioxide emission, but in the linear regression just for

petrol price and carbon dioxide emission shown in figure 3, this relationship is negative. One possible reason for this is because the range for petrol price is very small comparing with other variables so its relationship with total carbon dioxide emission is different under different scenarios. Since the effect of petrol price in the multiple linear regression model is our subject, the positively proportional relationship is taken and therefore H4 is satisfied.

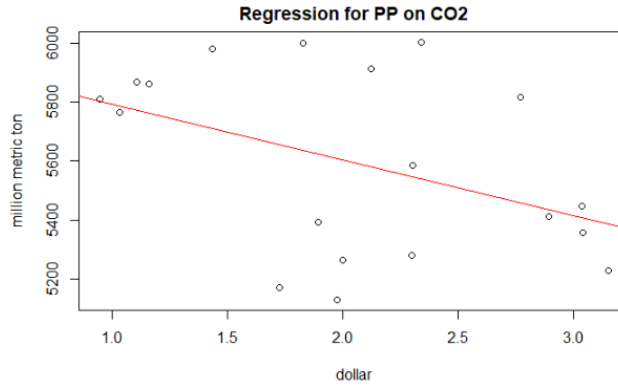


Figure 5 petrol price versus CO2 emission

4.6. ICEV sales

At last, the sales number of internal combustion engine vehicles has a positive but insignificant relationship with total carbon dioxide emissions. Its

coefficient is 1.523×10^{-5} but its t-value is insignificant at $\alpha = 5\%$. According to figure 6, the direct relationship between ICEV and CO2 is also not strong, but the general pattern is the same with the multiple linear regression model and H5 is satisfied.

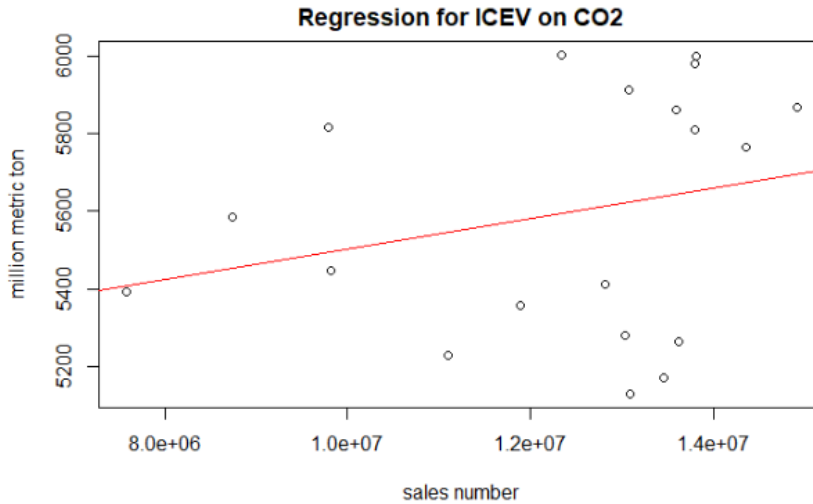


Figure 6 ICEV sales number versus CO2 emission

5. DISCUSSION

The results obtained from RStudio show that the significant factors affecting carbon dioxide emissions in the multiple linear regression model are: the sales number of EVs, the petrol price and transportation sector energy consumption; the insignificant factors are: electricity production, industrial sector energy consumption and sales of ICEVs. For the three significant factors, only the sales number of EVs is negatively proportional to carbon emission, the others are positive.

From the results of EV, we can see that the development and public appreciation of EVs generally follow the trend of reducing carbon dioxide emissions. Although causality cannot be concluded, it does seem that purchasing electric vehicles help reduce emissions. This claim can be further supported by TSC. Since TSC is an effective indicator of transportation sector GHG emissions, the positive relationship between TSC and

CO2 shows that transportation sector emission is decreasing along with increasing sales of EVs. Similarly, the positive relationship between PP and CO2 indicates that the demand for petrol is reducing and presumably less petrol will be consumed to produce GHG emissions.

For the insignificant factors, the most plausible reason is that the data is too big and general to describe the specific portion that relates that EV lifecycles. For instance, only a small portion of total electricity production is used to power EVs.

The greatest limitation of this study is that the range of data is too broad and unfocused. The lack of available data sources restricted the precision of the study. If more detailed data are presented, for instance, the industrial energy consumption specifically for battery manufacturing, then the credibility of the results can be improved greatly.

6. CONCLUSION

This study aims to investigate the relationship between the sales number of electric vehicles and the total carbon dioxide emission in the United States. Based on the data from 2000 to 2018, the multiple linear regression model suggests that there's a negatively proportional relationship between the two variables. Besides the sales of EVs, the energy consumption in the transportation sector and petrol price are also significant factors affecting carbon dioxide emissions.

The result of this study validates the general pattern that was proposed in the argument and provides insight into the potential environmental benefits of electric vehicles. Different from previous researches, this study answers the question regarding EVs' mission of reducing emissions in a macroscopic perspective. While a linear regression model is used for prediction, it is also possible to deduce causality with modifications on methodology and more detailed data. In future studies, more detailed aspects of EV-related carbon dioxide emission can replace the total, and more factors of EV lifecycle emission can be included so that a possible causality can be drawn. Moreover, investigations can be done to discuss the reason why some of the factors are insignificant in this content.

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