University Transportation Research Center - Region 2

Final Report

Effect of Plug-in Hybrid Electric Vehicle Adoption on Gas Tax Revenue, Local Pollution, and Greenhouse Gas Emissions

Performing Organization: Rowan University

December 2015

University Transportation Research Center - Region 2

The Region 2 University Transportation Research Center (UTRC) is one of ten original University Transportation Centers established in 1987 by the U.S. Congress. These Centers were established with the recognition that transportation plays a key role in the nation's economy and the quality of life of its citizens. University faculty members provide a critical link in resolving our national and regional transportation problems while training the professionals who address our transportation systems and their customers on a daily basis.

The UTRC was established in order to support research, education and the transfer of technology in the field of transportation. The theme of the Center is "Planning and Managing Regional Transportation Systems in a Changing World." Presently, under the direction of Dr. Camille Kamga, the UTRC represents USDOT Region II, including New York, New Jersey, Puerto Rico and the U.S. Virgin Islands. Functioning as a consortium of twelve major Universities throughout the region, UTRC is located at the CUNY Institute for Transportation Systems at The City College of New York, the lead institution of the consortium. The Center, through its consortium, an Agency-Industry Council and its Director and Staff, supports research, education, and technology transfer under its theme. UTRC's three main goals are:

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The research program objectives are (1) to develop a theme based transportation research program that is responsive to the needs of regional transportation organizations and stakeholders, and (2) to conduct that program in cooperation with the partners. The program includes both studies that are identified with research partners of projects targeted to the theme, and targeted, short-term projects. The program develops competitive proposals, which are evaluated to insure the mostresponsive UTRC team conducts the work. The research program is responsive to the UTRC theme: "Planning and Managing Regional Transportation Systems in a Changing World." The complex transportation system of transit and infrastructure, and the rapidly changing environment impacts the nation's largest city and metropolitan area. The New York/New Jersey Metropolitan has over 19 million people, 600,000 businesses and 9 million workers. The Region's intermodal and multimodal systems must serve all customers and stakeholders within the region and globally.Under the current grant, the new research projects and the ongoing research projects concentrate the program efforts on the categories of Transportation Systems Performance and Information Infrastructure to provide needed services to the New Jersey Department of Transportation, New York City Department of Transportation, New York Metropolitan Transportation Council , New York State Department of Transportation, and the New York State Energy and Research Development Authorityand others, all while enhancing the center's theme.

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LIST OF ABREVIATIONS AND SYMBOLS

CD	charge depleting
CDD	cooling degree days
CS	charge sustaining
CTPP	U.S. Census Transportation Planning Products
CV	conventional vehicle
eGRID	Emissions and Generation Resource Integrated Database
EIA	Energy Information Administration
EV	Electric vehicle
FERC	Federal Energy Regulatory Commission
FIPS	Federal Information Processing Standard
GHG	Greenhouse gas
GPS	Global positioning system
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model
HCHO	hydrocarbons
HDD	heating degree days
HEV	Hybrid electric vehicle
ICE	internal combustion engine
MPG	miles per gallon
MWP	mileage weighted probability
NMOG	non-methane organic gasses
NPTS	Nationwide Personal Transportation Survey
NTHS	National Transportation Household survey
PM	particulate matter
PPM	Parts per million
SUV	Sport utility vehicle
PHEV	Plug-in hybrid electric vehicles
UF	utility factor
VMT	Vehicle miles traveled
EPA	Environmental Protection Agency

EXECUTIVE SUMMARY

Plug-in hybrid electric vehicles (PHEV) are likely to increase in popularity in the near future. However, the environmental benefits of PHEVs involve tradeoffs between the benefits of reduced tailpipe emissions against the drawbacks of increased emissions at marginal electric generation plants and reduced gasoline tax income. In this report, a model is developed that will enable these tradeoffs to be studied. The model accounts for local commuting patterns and marginal electric generation in New Jersey. The result allows the effect of PHEV adoption on gasoline tax, CO_2, NO_x and SO_x to be predicted on a county level. Sample calculations are presented.

INTRODUCTION

The threat of climate change, combined with increased demand on natural resources is motivating advancements in alternative fuels and alternative fuel powertrains for vehicles. Potential alternative fuel pathways include biofuels, electric and hydrogen. Likewise, there are numerous platforms for alternative powertrains, e.g., all-electric, hybrid, plug-in hybrid. Various factors will affect the developments of alternative fuel passenger vehicles, including technical advancements, costs of fuel sources, development of infrastructure, policy decisions, and consumer acceptance. These factors make it difficult to predict the long-term future of vehicle power trains. However, plug-in hybrid electric vehicles (PHEV) which can be recharged via the electric grid or through an onboard gasoline powered generator, are well positioned to be widely adopted in the near future. They have an obvious path to market as they do not require significant infrastructure investments, will likely be cost-effective in the near term, and adoption would make meaningful greenhouse gas (GHG) emission reductions.

However, analysis of the environmental benefits of hybrid electric vehicles is especially complex. Two factors contribute to their complexity. First, when they are operating from batteries that were charged from the grid, the effective emissions are from the plant that generated the electricity, not the tailpipe of the vehicle. Therefore, not only the area that a vehicle is driven in is affected by PHEV travel. Furthermore, the emissions resulting from electric generation are dependent on the type and efficiency of the plant, and can vary greatly. Second, as PHEV's can operate in two different modes, the distance traveled between recharging can have a significant impact on the emissions. These two factors combine to make the emissions from PHEV's dependent on place in a manner that is not well accounted for in standard methods for tracking vehicle emissions.

Problem Statement

The purpose of this study is to develop a model to account for the effect of local commuting patterns and electric generation to predict the effects of PHEV adoption in New Jersey. The model accounts for commuting patterns on a county by county basis, and considers emissions from both tailpipes and marginal electric generation throughout the state during both normal and peak times of demand.

While the environmental implications – both in terms of GHG and local particulate and gaseous emissions – of significant market penetration are important, we must also consider the implications for state gasoline tax revenues and additional emissions from electric generation plants when the fuel pathway for vehicle travel is shifted from gasoline to the electric grid. GHG emissions from PHEVs are highly correlated with the source of electricity used, and emissions such as nitrogen and sulfur oxides lead to localized conditions, affecting some areas more than others. This model analyzes the impact of PHEVs at a county level to observe these local effects.

The model will provide policy makers with data to better evaluate these tradeoffs within the region. Appropriate responses might include modification to the structure of transportation funding, changing the extent to which recharging infrastructure is encouraged throughout the state, or recommending best practices for recharging.

Literature Review

Vehicle Selection

Granovskii1 lists the following criteria for economic comparisons of vehicles: vehicle price (including cost to change battery for EVs), fuel costs, and driving range. The authors compare multiple vehicle power sources, and while no PHEVs were available in market at the time of the study, they used the Toyota Corolla as their baseline conventional vehicle.

Several studies simulate PHEV characteristics with models. Thomas2 used the average relative fuel economy estimates from four studies: the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model, The Auto/Oil report led by GM and Argonne National Laboratory, the MIT study on electric drive trains, and the National Research Council report on hydrogen. Silva3 and Parks4 both use the ADVISOR model developed by the US Department of Energy to model design characteristics of idealized PHEVs. The Electric Power Research Institute (EPRI) Environmental Assessment of Plug-In Hybrid Electric Vehicles5 uses the Mobile Source Emission Factor Model (MOBILE6) to model nationwide fleet emissions. MOBILE6 contains vehicle miles travelled (VMT) data for the contiguous United States and 28 different vehicle classifications, as well as "real-world" fuel economy data per vehicle classification. Other sources of data include the EPRI's prior analysis "Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options and Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options for Compact Sedans and Sport Utility Vehicles" and the Emissions Factor Model (EMFAC), the MOBILE6 equivalent preferred by the state of California. In this study, a hybrid electric vehicle is assumed to have 35% lower fuel consumption than a conventional vehicle, which is a number in line with simulated and EPA-certified differentials between conventional and hybrid vehicles. Williams6 used the MY2009 fleet-wide real-world average to represent the mpg (and therefore emissions) of a conventional vehicle. Zhang7 uses the General Motors EV 1 drivetrain with a Toyota Prius' mass and aerodynamic coefficient in an ADVISOR simulation to simulate their model PHEV. They use a 25MPG gasoline powered vehicle as their baseline CV.

Other studies take characteristics from specific, commercially available models. Lave and MacLean8 compared the Toyota Prius to its conventional fuel counterpart the Toyota Corolla. Samaras and Meisterling9 considered PHEVs with attributes similar to the Toyota Prius, with additional battery capacity to enable plug-in capabilities in a parallel configuration, on the assumption that the introduction of a sedan PHEV will build upon an existing HEV design. They compare this PHEV to the Toyota Corolla, citing the work of Lave and MacLean and the similarities in characteristics, dimensions, and curb weight of the two vehicles. Stephan and Sullivan[10] use an AE-40 with the characteristics of a Toyota RAV-4 SUV EV, which was commercially available in 2003.

Commute Data

Because the census commuter data are given in travel times and locations, it is necessary to convert that information to vehicle miles to analyze emissions and displaced gasoline. Rietveld[11] discusses the relationship between reported travel time from surveys, distance as the crow flies, network distance (actual distance along roadways) and network time as calculated by a global positioning system (GPS) device. The authors suggest that there are three speed regimes (for near, medium and far trips) that account for the non-linear relationship between network time and network distance, determined by the share of types of roads on a given trip. Results indicate the need for a constant term for estimating travel time, especially at short distances. Rietveld also discusses the error associated with estimating trips by centroid of a general location (county, town, worksite), and how that error becomes expectedly less significant as trip distance increases. Kang and Recker[12] mentions two methods for estimating the driving distance between two points. The "Euclidean-based" method is the distance as the crow flies between the origin and destination, and the "Manhattan-based" method computes driving distance as the sum of the latitudinal and longitudinal differences between the two points. The authors used the latter method to calculate distances for their analysis, as it is an upper bound for travel distance and therefore shows the greatest potential impact. It is noteworthy to add that the difference in average daily mileage calculated using each method, and so the difference between upper and lower bound for calculating the average distance was only 23%.

One challenge of particular interest when analyzing the emissions impact and gasoline displacement of PHEVs is the need to separate miles driven in charge depleting (CD) mode, when the vehicle is powered by the electric battery, from miles driven in charge sustaining (CS) mode, when gasoline is used to power the drivetrain. Graham[13] uses mileage weighted probabilities (MWPs) derived from the US Department of Transportation's 1995 Nationwide Personal Transportation Survey (NPTS) to calculate an average for vehicle miles displaced by a PHEV operating in CD mode. Two methods were used to calculate the MWPs, one by the Electric Power Research Institute (EPRI) and the utility factor (UF) method developed by the SAE J1711 subcommittee. According to Elgowainy[14], Vyas[15] investigated this method but was unable to determine how the MWPs were developed. Additionally, Vyas updated the UF method when the 2001 NHTS data became available and partitioned the national average vehicle miles travelled (VMT) into miles that could be driven in CD mode and miles driven in CS mode. Williams[6] obtained driver behavior information from GPS, surveys, and driver exit interviews in a three-month study in Northern California. When compared to data from the NHTS, the study sample would require PHEVs with a larger CD range than national averages. This may indicate that average travel distance varies significantly between regions. Axsen and Kurani[16] developed a survey to collect data from new car buyers in California. Information on driving behavior as well as consumer preference for vehicle charging were considered and incorporated into a model to determine VMTs in each mode. Ernst[17] uses data on the driving behavior of the average gasoline-powered vehicle user in Germany obtained from a large field study to estimate total cost of ownership of a typical PHEV. Zhang7 uses data derived from the NHTS 2009 survey, using detailed trip information for one day for each sampled vehicle to estimate gasoline and emissions reductions from PHEV integration under several different charging scenarios.

<u>Electric Dispatch</u>

Several studies have used electric generation dispatch models to simulate the addition of PHEVs into a region's electrical grid. A dispatch model accounts for the need to utilize less cost-efficient cycling generators on top of the baseload electric generation to meet hourly demand. Studies using dispatch models include EPRI5, Parks4, Hadley and Svetkova[18], Axsen[19], and Sioshansi and Denholm[20].

Hadley and Tsvetkova gives load duration curves for energy demands in summer, winter, and off-peak seasons. Axsen uses annual average and marginal emissions rates. Sioshansi and Denholm tracks most pollutants annually, while NO_X emissions are calculated in ozone season (May through September) and non-ozone season (all other months).

Charging scenarios

Several studies have used various charging scenarios to determine PHEV impact on electricity demand. Throughout the literature, four different recharging scenarios are often considered.

1. Uncontrolled home charging: Charging exclusively at home, with no regulation on charging time. Vehicle begins charging when the driver returns home from their final trip, and stops when finished charging. This is the case of Weiller's[23] "at home only", Parks'4 "uncontrolled charging", and Zhang's7 "immediate home charging" scenarios.
2. Delayed home charging: Delays at-home charging until a certain time when the additional load will not affect the daily peak load. Charging was delayed until 10pm in Parks4. Axsen[19] calls this "off-peak only", representing this scenario as a constant load between 8pm and 6am. Zhang's7 delayed charging begins at 5:00am and ends at 9:00am. Duvall5 uses an approach that places 76% of charging between 10pm and 6am, with the remaining 24% during midday from workplace and daytime public charging.
3. Off-Peak charging or "Valley Fill" method: Electricity is dispatched to charging vehicles at moments of minimum system demand. This method is used in Parks4 and Denholm and Short[21]. Valentine[22] proposes a variation on the "valley fill" method, which accounts for the ramping cost of adding and removing generators, assigning 20% of the load to shoulder and peak hours.
4. Plug and Play Charging: Car is charging wherever and whenever it is not in motion. Allows for minimization of gasoline usage. Studies provide various assumptions on where a driver can recharge. In Parks4, vehicles are assumed to have access to an outlet wherever they are parked. Axsen[19] separates this scenario into two cases: One ("plug and play") that models charging whenever drivers are parked within 25ft of an outlet (based on survey data collected from study participants), and a second ("universal workplace access") that assumes drivers can charge at work regardless of whether they identified a nearby outlet or not. Weiller[23] also uses two continuous charging cases, one where drivers charge at home and at work, and another scenario that additionally allows drivers to charge in shopping centers.

Three charging scenarios are used in this model: Uncontrolled, where commuters arrive home and immediately begin charging; Delayed, where initial charging is delayed until some time when the peak will not be affected; and a "plug and play" scenario that assumes commuters will be able and willing to charge at work as well as home. Uncontrolled charging is the most logical charging method that would occur if no incentives were offered to consumers as it is assumed to be the most convenient method (as drivers would most likely plug in upon parking in their garage). Delayed charging was found to be the most effective method for reducing greenhouse gas emissions in Axsen[19] and requires no additional infrastructure. The "plug and play" approach of assuming charging at work would be the most aggressive scenario for displacing gasoline.

Current PHEV Market

PHEVs have seen a sharp increase in sales since their initial mass commercial availability in 2011 as major automotive companies began production. Total PHEV sales increased 80% from 2012 to 2013 and the latest year-to-date data (July 2014) shows an additional 60% gain over 2013.

There are four significant leaders in the current PHEV market: Chevrolet's Volt (38.47% of all PHEV sales in July 2014), Toyota's Prius Plug-in (23.89%), and Ford's Fusion Energi and C-Max Energi (combined 35.84%)[24]. The Toyota Corolla is considered as a baseline combustion engine vehicle. Table 9 shows relevant attributes of these vehicles.

Table 9. Side-by-side comparison from fueleconomy.gov[25]

2014 Model	CD Range	Elec + Gas Fuel Economy	Reg. Gas	Battery Size
Chevrolet Volt	38	35kWh/100mi	37 mpg	16 kWh
Ford C-MAX Energi	20	.0gal/100mi + 37kWh/100mi	38 mpg	7.6 kWh
Ford Fusion Energi	20	.0gal/100mi + 37kWh/100mi	43 mpg	7 kWh
Toyota Prius PHEV	11	.2gal/100mi + 29kWh/100mi	50mpg	4 kWh
Toyota Corolla	N/A	N/A	31 mpg	N/A

The Chevrolet Volt is classified by General Motors (GM) as an "electric vehicle with gasoline powered range-extending capability."[26] The Volt operates in all-electric mode until the battery reaches a certain low charge threshold (30%). When the low charge threshold is reached, the internal combustion engine (ICE) activates to recharge the battery. This drive train is unique, because the ICE never delivers power to the wheels. It only is used as a generator to charge the battery, while the electric motor drives the vehicle.

The Toyota Prius Plug-In Hybrid's drive train operates in "EV Mode" while the battery is charged. EV Mode is a blended hybrid mode in which the electric motor is supplemented by an ICE only in high stress situations (hard acceleration or high speeds). When the battery is depleted, the Prius Plug-In operates in "hybrid mode", behaving like a traditional Prius using the ICE and electric motor.[27]

Both the Ford Fusion Energi and C-Max Energi operate as blended hybrids, just as the Toyota Prius. However, when run in "EV Now" mode, the Ford PHEVs operate in all-electric mode for about 20 miles of driving before switching to the ICE. Both vehicles use power from the internal combustion engine when necessary, but use the electric motor for all normal/low demand driving.[28]

Because the Chevrolet Volt is the market share leader, and because its lack of a blended hybrid mode allows for a simpler model, it was chosen for this study along with a popular conventional vehicle with similar characteristics, the Toyota Corolla. As the study focuses on a present-day analysis, using presently-available vehicles will best represent the immediate impact of conventional vehicle fleet integration.

Approach

Commutes account for under 30% of total vehicle miles travelled (VMT) according to the 2009 National Transportation Household Survey[29]. However, commutes are a constant and simple to predict source of vehicle miles. The authors also believe that commute distance is a prime consideration for those considering purchasing a PHEV, as users would most likely consider commute distance related to all-electric range to inform their decision. According to Tal et al[30], commute distance has a significant impact on total PHEV miles, with over 70% of PEV owners using their vehicle for the purpose of commuting.

The U.S. Census Transportation Planning Products (CTPP) 5-year data (2006-2010)[31] contains information on commuting flows on the state, county, and municipality levels. As the CTPP dataset does not contain information on commute distance, road network distance between each municipality in the scope of the study was determined using online distance matrix mapping software. This information was used to develop a database of New Jersey commuter behavior outlined in the next section. Once the distance of each commute was determined, miles driven were separated into distances in CD and CS mode. From there, volume of gasoline displaced was calculated based on MPG of the representative conventional vehicle (CV), the Toyota Corolla.

Using Emissions and Generation Resource Integrated Database (eGRID)[32] information and daily report data from the Federal Energy Regulatory Commission (FERC) as input, a baseline dispatch model for electric generation in New Jersey with no PHEVs was developed. This baseline load is compared to different PHEV fleet integration and charging scenarios to analyze the impact of PHEVs on emissions and electricity cost. Following Hadley and Tsvetkova[18], the model accounts for summer, winter, and 'other' seasons.

Using the commute distance database and this electricity dispatch model, a number of miles driven per county by the representative CV, PHEV in CD mode, and PHEV in CS mode may be modeled for a given scenario, the kWh required to charge the PHEV may be calculated, and their respective contribution to emissions per county may be tracked.

DEVELOPMENT OF MODEL

The model is developed by considering the available commuter data to determine the number of miles driven in each county, and by utilizing a dispatch model to attribute specific utility plants in New Jersey to marginal electric use. Once these are determined, emissions attributed to both vehicle tailpipes and electric generation are assigned to appropriate counties.

Commutes

A database that describes commutes between municipalities in New Jersey in terms of both the number of commutes and the distances of the commutes was developed. The form of these data is a 3 dimensional array, Bin(i,j,k). The value of the [i,j,k] cell of the array is the number of commutes of a distance between 5*(k-1) and 5k miles that begin in county i and conclude in county j.

Two data sources were used to obtain the necessary data for commuter analysis: the CTPP 5-year data sorted by county and municipality, and an online mapping application. The CTPP data gives number of daily commute trips from any origin to any destination, and these origin-destination pairs were input into online mapping software to obtain total vehicle miles between municipalities.

The data were converted to a distribution of distances for commutes between two given counties, i and j, in the following manner. First, the CTPP data were used to develop a matrix Trips(i,j,k,l) that characterizes the total number of commutes from each municipality in county i to each municipality in county j. Next, the mapping software was used to develop a matrix Miles(i,j,k,l) that characterizes the distance between each municipality k in county i to each municipality l in county j. These matrices follow the following format:

Miles(i,j,k,l) =**Distance**
Trips(i,j,k,l) **=# of Trips**

Where:
i = origin county
j = destination county
k = origin municipality
l = destination municipality
i,j = FIPS naming convention
k,l = municipalities assigned numerical order based on alphabetical order

The Federal Information Processing Standard (FIPS) naming convention[33] is used for all counties and allows for ease of indexing and obtaining data. See Figure 9 for a graphical representation of the indexing of data.

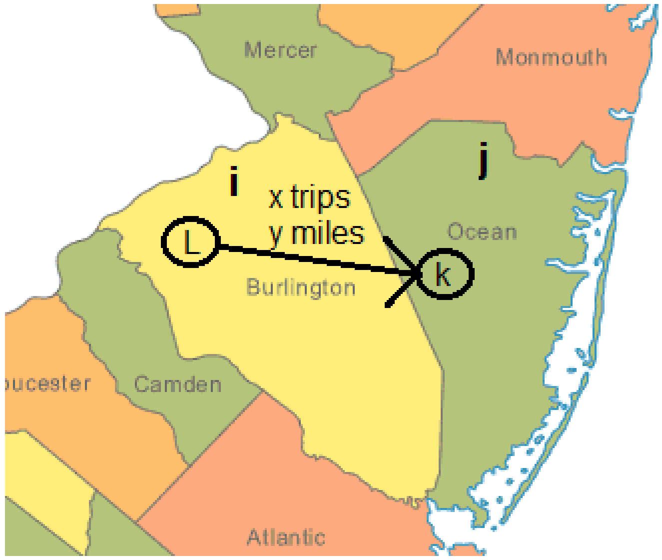

Figure 9. A hypothetical index for clarity purposes, showing a commute from county i, municipality L, to county j, municipality k results in the distance of that commute, y, and how many vehicles make that commute daily, x

The data were divided into bins of distance distribution by number of people who make a specific range of distance commutes to compare commutes on the county level. This was done using a Matlab script that passes through each iteration of both the Miles(i,j,k,l) matrix and the Trips(i,j,k,l) matrix. The number of trips were summed and sorted based on their corresponding distance matrix index. The Bin matrix follows the following format:

Bin(i,j,m) = # of trips from county i, to county j, for distance bin m

This distribution can be observed for all possible county-to-county combinations. Each bin represents intervals of distance of commute, starting at 0 miles and increasing by increments of 5 miles. Figure 10 is an example county-to-county commute distance distribution.

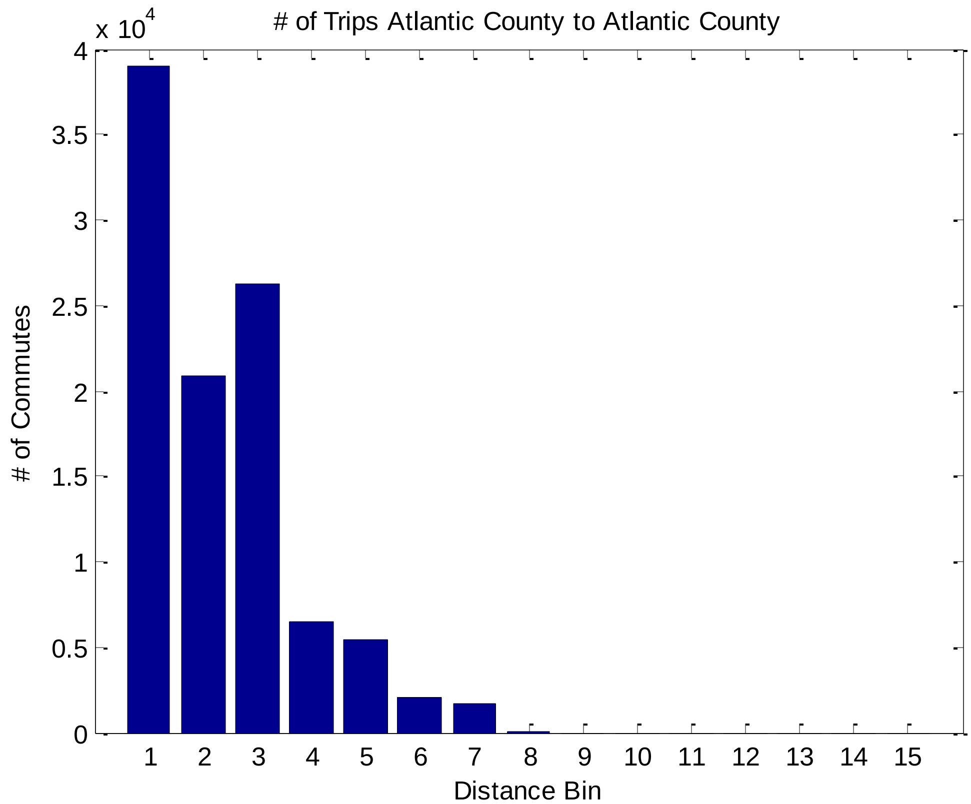

Figure 10. Distribution of distances traveled by all vehicles commuting from Atlantic County to Atlantic County

These distributions are then used to analyze and study PHEV use on a county level. In addition to modeling commutes state-wide, the data can be analyzed at a county or regional level to determine the impact of shifting emissions, as well as gasoline consumption and gasoline tax revenue.

Attributing Vehicle Miles to Counties

In the event that a trip is made between multiple counties, the miles are attributed equally between them. Trips that must cross multiple counties were chosen by least number of counties crossed. Since it was assumed that commuters would choose paths that require the least number of miles traveled, not necessarily the least number of counties crossed, some paths were manually edited and re-entered. Out-of-State paths were also edited to account for bridges and interstate highways not included in the automatically generated data.

Out of State Commutes

13% of commutes originating in the state of New Jersey have out of state destinations[31]. The vast majority of these commutes end in New York and Pennsylvania (72% and 23%, respectively). According to the CTPP data, 92.5% of commutes from New Jersey to New York State are to New York City, and 60% of commutes to Pennsylvania are to Philadelphia. The number of commutes to Delaware and other states represents less than 5% of the commutes leaving New Jersey.

Since only 60% of the commutes to Pennsylvania are destined for Philadelphia, the Pennsylvania counties surrounding the city were taken into consideration. 13% of these commutes are to Bucks County, 7% to Delaware County, and 10% to Montgomery County. This greater Philadelphia area accounts for 90.8% of commutes from New Jersey to Pennsylvania.

Electric Generation and Demand in NJ

According to the EIA profile analysis of New Jersey[34], over one-half of net electricity generation in the state is supplied by nuclear energy. Natural gas makes up the next largest share, with coal and renewable sources accounting for less than one-tenth of in-state generation. Nearly one-third of New Jersey's electricity is supplied by generators in other states.

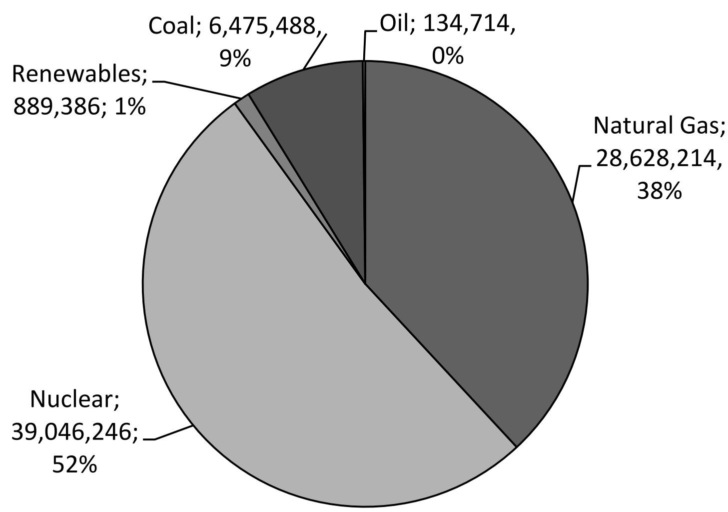

Figure 11. New Jersey energy generation (MWh) by fuel type (adapted from New Jersey 2011 Energy Master Plan)[47]

<u>Determining Average Electrical Grid Load Based on Weather</u>

The average electrical grid load for New Jersey during three characteristic days based on the weather was found. The characteristic days are intended to reflect the heating season, the cooling season, and the neutral temperature season. Use of these three characteristic seasons has been adopted by several other researchers as well[18,21]. Both cooling and heating degree day data were gathered and analyzed. Degree days are a measure of the heating/cooling required to maintain a predetermined base temperature[35]. The base temperature used for this analysis was 65°F for both the cooling and heating degree days. The data are for Trenton, NJ (central location in NJ) over a 13 year period from 2000 to 2013.

The data were divided into heating degree days (HDD) and cooling degree days (CDD) for each month throughout the 13 year period. The average values for the months were then divided by the number of days in the month to find the average daily HDD and CDD values for each month. The average values for each month over the 13 year span can be seen in Table 10. To represent all seasons, the two most extreme months, reflected by the greatest heating and cooling requirements, and the most moderate month, reflected by the least combined heating and cooling requirements, were identified. The coldest month is January, with an average of 34 HDD/day. The warmest month is July, with an average of 10 CDD/day. The mildest month is September, with averages of 3 CDD/day and 2 HDD/day.

Table 10. Average values of heating and cooling degree days per day and per month by month

	Cooling Degree Days		Heating Degree Days	
	Per day	**Per month**	**Per day**	**Per month**
January	0	0	34	1053
February	0	0	31	889
March	0	0	23	726
April	0	0	13	399
May	2	35	5	158
June	6	166	0	9
July	10	305	0	1
August	8	266	0	2
September	3	91	2	48
October	0	8	10	320
November	0	0	20	588
December	0	0	30	917

Once the three characteristic months were identified, a single day in each of these months was chosen to represent the month. The specific days were chosen to best reflect the average HDD and CDD for the intended month. Furthermore, the specific days were further constrained to not be either weekend or holidays, so as to reflect typical work days. Weather Underground's "Historical Weather" information was used to find the individual day data for 2010[36]. The days were selected based on the DD values and being normal workdays (no weekend or holidays), and were June 19th, January 12th, and September 10th.

Electrical demand figures were obtained for the selected days from the Federal Energy Regulatory Commission (FERC) website[37]. The actual electric demand information from FERC is only available by service region, not state. The procedure for estimating New Jersey electric demand is outlined in appendix B.

A proportion was calculated of the ratio of people in New Jersey (8,791,894) to the number of people in the Mid Atlantic Region (24,083,686). This proportion suggests that New Jersey uses 36.51% of the total electricity used in the Mid Atlantic Region. Final electrical usages for New Jersey were calculated by multiplying the above ratio by the usages of the Mid Atlantic Region. Figure 12 shows the New Jersey electricity usage for the three selected days versus time of day. The minimum and maximum load for each selected day can be seen in Table 11.

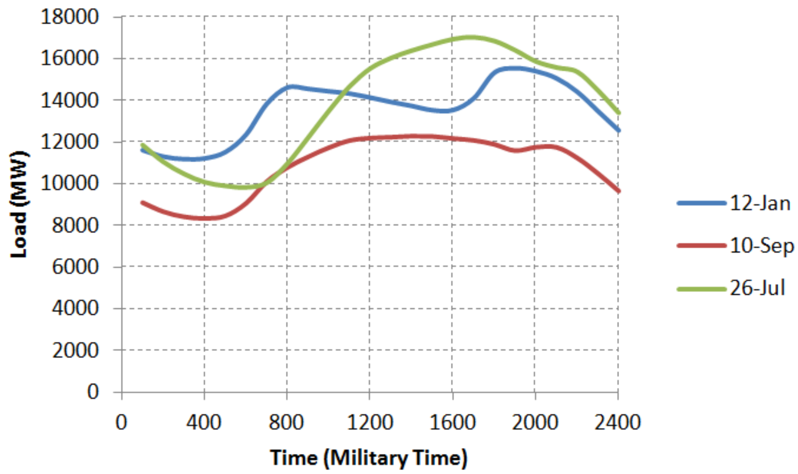

Figure 12. Electrical usage of New Jersey versus time of day for three days of varying weather conditions in 2010.

Table 11. Minimum, maximum, and average load for three days of varying weather conditions in 2010.

Day	Load (MW)		
	Maximum	Average	Minimum
January-12	15535.74	13560.76	11165.85
July-26	17012.56	13792.58	9833.60
September-10	12297.30	10830.72	8352.39

Electric Supply

A dispatch model for electricity supply was developed to determine the marginal source of electricity for additional electric demand that might be created due to PHEV recharging. The construction of a dispatch model involves comparing the pre-existing capacity from power plants in New Jersey to the demand for electricity throughout the state.

Additional demand caused by PHEV charging on the above three days simulates an extra electricity supply that would need to be generated. The capacity of all the power plants in New Jersey is considered to determine the electric supply. Additionally, New Jersey purchases approximately one-third of its electricity to meet its yearly demands[34].

The dispatch model divides the supply for New Jersey into two separate parts: non-dispatchable and dispatchable power plants. The non-dispatchable plants consist of plants that run on nuclear, solar, wind, hydro, and biomass power, along with cogeneration companies and refineries. These are the plants that are most effective at providing power all the time due to their low variable costs of production. Non-dispatchable plants are constantly running and producing a specified amount of electricity, therefore adding extra PHEV charging demands would not affect the production rate at these plants. Conversely, dispatchable plants are called to come on a significant portion of the year to meet each seasonal demand. The dispatchable plants include the power plants that run on coal, oil, and natural gas. These plants cycle on and off, depending on the demand for a particular time.

Adding additional PHEV charging demand would affect the electricity production for the dispatchable plants. These plants would be required to cycle on to account for the extra demand. The dispatchable plants can be broken into classes depending on the cost of fuel per kWhr each plant uses to produce electricity. The plants that have the lowest fuel costs will be called on first to meet extra demand. Determining the extra fuel source used for a certain demand value will help to measure emissions at the plant level. A list of dispatchable plants, their fuel sources, and fuel costs may be found in appendix C1. The top 15 non-dispatchable power plants (by capacity) that contribute the most electricity to meet the demand are shown in appendix C2. All non-dispatchable sources are accounted for in the model. Data acquired from eGRID for the year 2010 was organized and tabulated to determine the supply portion of the model[32]. The eGrid database provides information on power plants in the United States, including the plants' power usage, fuel source, and capacity factor. The capacity factor indicates how much electricity a generator produces relative to the maximum it could produce at full capacity in a given year of operation[38]. After collecting data from eGrid, the fuel cost for dispatchable plants was determined. The cost for each fuel source was found from the EIA[52] and converted to fuel cost per kilowatt hour for each power plant.

These costs are plotted against capacity factor in Figure 13 for each plant in New Jersey. Because fuel cost is the predominant factor in determining marginal generation cost, this figure helps determine which generators would be dispatched first. Plants with fuel costs below $0.05/hWh have a wide range of capacity factors, suggesting that these plants are cycled on and off interchangeably. There is a group of plants that have fuel costs at $0.05 or greater that have capacity factors well below 0.1. Based on this observation, plants are divided into a group of dispatchable plants for typical demand, and a group of dispatchable plants for peak demand.

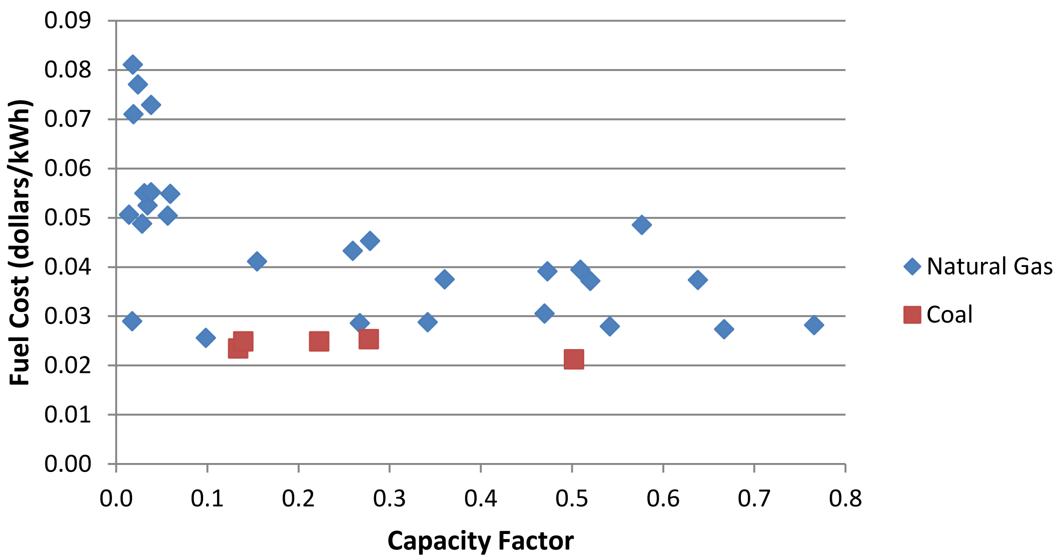

Figure 13. Dispatchable power plant fuel cost by capacity factor and fuel source

By comparing the dispatchable, non-dispatchable, and purchased demand to the data acquired from the Federal Energy Regulatory Commission (FERC) shown in Figure 12, a visual representation of each of their contributions to total supply was created and is plotted in Figure 14.

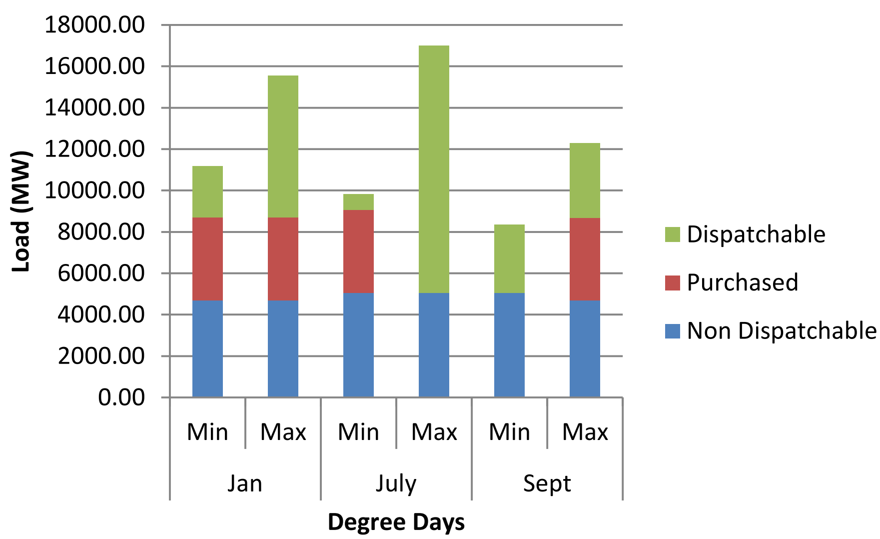

Figure 14. Graphical representation of electric supply generated from dispatchable, non-dispatchable, and purchased electricity to meet the maximum and minimum demand of the three representative days.

The blue portion of the graph represents the supply generated by non-dispatchable plants that provide the baseload energy. This amount represents the total of the capacity times the capacity factor for all non-dispactable plants in New Jersey. The one exception to this is that a capacity factor of 1.0 is used for the month of July. This assumes that nuclear plants are not brought offline for maintenance during the summer months. The red portion of the graph represents the purchased out-of-state electricity, which is approximately one third of New Jersey's yearly average. During the maximum demand in July and the minimum demand in September, it is assumed that New Jersey is not purchasing any additional electricity. This is because during high-demand periods, the price to purchase per kilowatt of electricity rises significantly, and it is more cost efficient to cycle on even the most expensive dispatchable plants. During low demand periods, the dispatchable and non-dispatchable power plants can produce enough electricity to meet demand, and purchasing additional electricity is not cost efficient. Lastly, the green portion of the graph represents the power generation attributed to dispatchable plants that are used to meet the remaining. By analyzing Figure 14, the dispatchable capacity that is contributing to the total demand can be related to the cost to meet the demand during each seasonal period. This trend can be seen in Figure 15.

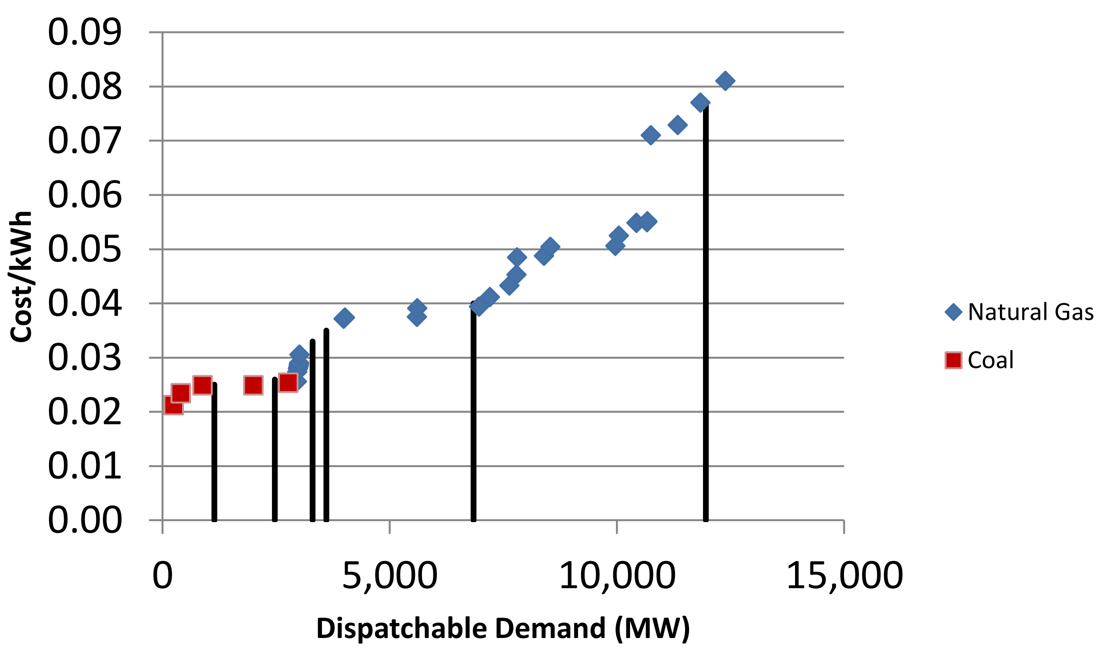

Figure 15. Cost and dispatchable supply. The black lines represent the supply needed to meet the min and max demand for each of the three representative months

Figure 15 demonstrates that throughout the year, most of the dispatchable demand will fall between 1,500 to 4,000 megawatts of power, which will cost between \$0.02 and \$0.04 on average. The price of fuel will increase during the hottest days of the year, where the demand is at a maximum. As this period of high demand will affect all regions, the price to purchase electricity is especially high. As a result, it is assumed in the model that companies do not purchase electricity during the times of highest demand. Determining the fuel source that each power plant will use to meet certain demands will aid in attributing the additional emissions cost from charging plug-in hybrid electric vehicles.

Emissions

The categories of pollutants monitored for electric generation and gasoline tailpipe emissions do not overlap completely. Carbon Dioxide (CO_2) and other equivalent greenhouse gases, nitrogen oxides (NOx), and sulfur oxides (SO_x) are monitored for electric generation, whereas CO_2, NOx, particulate matter ($PM_{2.5}$), non-methane organic gasses (NMOG) and hydrocarbons (HCHO) are monitored for tailpipe emissions. Therefore, only CO_2 and NO_x emissions can be compared directly. In both combustion cycles, NO_x is produced by Nitrogen in the air being oxidized through the heat of the reaction. The CO_2 in both cycles can be directly compared through the amount of fuel burned per mile driven or kWHr generated.

Vehicle Emissions

The average carbon dioxide emission for gasoline combustion is 8,887 grams CO_2/gallon[39]. This value is divided by the miles per gallon of the respective representative vehicles to obtain 287g/mi for the Toyota Corolla and 240g/mi for the Chevy Volt.

The 2015 Toyota Corolla is certified as a Tier 2 Bin 5 vehicle by the EPA exhaust emissions standards, and the 2015 Chevrolet Volt is certified Tier 2 Bin 3**Error! Reference source not found.**. EPA emissions standards for light duty vehicles are shown in Table 12.

Table 12. Federal Tier 2 light duty vehicle exhaust emission standards Error! Reference source not found.

Standard	Emissions Limits at 50,000 Miles					Emission Limits at Full Useful Life (120,000 miles)				
	NOx (g/mi)	NMOG (g/mi)	CO (g/mi)	PM (g/mi)	HCHO (g/mi)	NOx (g/mi)	NMOG (g/mi)	CO (g/mi)	PM (g/mi)	HCHO (g/mi)
Bin 1	–	–	–	–	–	0	0	0	0	0
Bin 2	–	–	–	–	–	0.02	0.01	2.1	0.01	0.004
Bin 3	–	–	–	–	–	0.03	0.055	2.1	0.01	0.011
Bin 4	–	–	–	–	–	0.04	0.07	2.1	0.01	0.011
Bin 5	0.05	0.075	3.4	–	0.015	0.07	0.09	4.2	0.01	0.018
Bin 6	0.08	0.075	3.4	–	0.015	0.1	0.09	4.2	0.01	0.018
Bin 7	0.11	0.075	3.4	–	0.015	0.15	0.09	4.2	0.02	0.018
Bin 8	0.14	0.100 / 0.125[c]	3.4	–	0.015	0.2	0.125 / 0.156	4.2	0.02	0.018
Bin 9[b]	0.2	0.075 / 0.140	3.4	–	0.015	0.3	0.090 / 0.180	4.2	0.06	0.018
Bin 10[b]	0.4	0.125 / 0.160	3.4 / 4.4	–	0.015 / 0.018	0.6	0.156 / 0.230	4.2 / 6.4	0.08	0.018 / 0.027
Bin 11[b]	0.6	0.195	5	–	0.022	0.9	0.28	7.3	0.12	0.032

SO_x emissions are not monitored in vehicle tailpipe emissions due to the relative sulfur purity of modern gasoline. Gasoline is regulated to have an average sulfur content of 30 PPM and not to exceed 80

PPM[42]. Through a volumetric calculation of sulfur emissions released per mile driven for the Toyota Corolla, the value is roughly .002g/mi.

$$\left(\frac{1*10^6\ g\ gasoline}{30\ g\ sulfur}*\frac{cm^3}{.7\ g\ gasoline}*\frac{1\ L}{1000\ cm^3}*\frac{gal}{3.785\ L}*\frac{32mi\ driven}{gal\ gasoline}\right)^{-1}=\frac{.002\ g\ sulfur}{mi\ driven} \tag{1}$$

This value is an upper limit, and will improve with future gasoline restrictions in 2017. It is negligible compared to other gasoline emissions and is ignored.

Gasoline vehicles emit almost negligible amounts of particulate matter (PM) until engine wear sets in[43]. Because this study compares a new conventional vehicle to a new PHEV, PM emissions for vehicles are not tracked.

<u>Emissions from Power Plants</u>

Emissions rates for dispatchable plants by generating station for the three tracked pollutants ($CO_{2\text{-equiv}}$, NO_x, and SO_x) can be found in Appendix A.

Particulate matter from electric generation can be separated into two categories: filterable and condensable. Filterable particulate matter can be filtered or scrubbed before it is released into the atmosphere and is emitted at a rate of nearly zero for power plants. Condensable particulate matter is a collection of hydrocarbons that condense in the cooling stacks into PM, and are emitted at a significant rate for coal power plants.

According to the Energy Information Administration (EIA), natural gas produces 7lbs of $PM_{2.5}$ per billion Btu of energy input**Error! Reference source not found.**. The calculation below results in only 0.011g/mi when using the characteristics of the Chevy Volt.

$$\frac{7lb}{1*10^9Btu\ Input}*\frac{1027Btu}{1ft^3}*\frac{10ft^3}{1kWh}*\frac{.35kWh}{1mi}*\frac{453.59g}{1lb}=\frac{.011g}{mi\ driven\ electrically} \tag{2}$$

According to the EPA national emissions inventory, the electric utility sector makes up 2% of New Jersey's total PM_{10} and 3% of $PM_{2.5}$ emissions[45]. Because so few particulate matter emissions are from electric generation, even aggressive PHEV implementation scenarios result in a negligible change in statewide particulate matter emissions.

While mercury is produced in the burning of fossil fuels for energy, the amount generated by natural gas power plants is negligible. The total mercury output in 2011[46]45 for all of New Jersey's coal generators was less than 100 pounds, down 90% after strict regulations were imposed in 2005. As the charging of PHEVs in even extreme scenarios in the model requires a low amount of energy relative to the entire

New Jersey electric load, and because coal makes up less than 10% of New Jersey electric generation, it is not tracked in this model. It is worth noting that the addition of PHEVs would undoubtedly cause a minor increase in net mercury emissions in the state.

Overview

An overview of emissions accounted for in the model is shown in Table 13.

Table 13. Relevant emissions by source

Emission	Vehicles	Electric Generation
CO_{2equiv}	X[A]	X[B]
NO_X	X[C,D]	X[B,C]
SO_X		X[B,C]
CO	X[C, D]	
HCHO	X[C]	
NMOG	X[C]	
$PM_{2.5}$	X[C,D,E]	
PM_{10}	X[C,D,E]	
Mercury		X[E]
Formaldehyde	X[C,F]	

Local emissions are tracked at the county level by attributing gasoline emissions from miles driven in that county. Because carbon dioxide is an atmospheric pollutant, it is not meaningful to track CO_2 at the local level, and is only calculated as a global total for the purposes of summing net change in CO_2.

RESULTS AND DISCUSSION

The model can be used to analyze the net effect on emissions due to replacing conventional vehicle commutes originating in a chosen NJ county with PHEV commutes. Changes in CO_{2equiv}, NO_X, CO, HCHO, SO_X, and non-methane organic gasses are tracked.

It is important to consider the net effect from both vehicle use and electric generation. In general, total CO_2 and NO_x is lowered by implementation of PHEVs. Naturally, any vehicle-specific emissions decrease while SO_X increases. However, somewhat counter-intuitively, emissions in a specific county may

[A] Not tracked by EPA, but included in model
[B] Tracked by EPA Emissions and Generation Resource Integrated Database (eGRID)
[C] Included in EPA light duty vehicle standards
[D] EPA criteria pollutant
[E] Upper bound estimate made – neglected in model
[F] Not considered

increase despite net reduction from a given scenario. Table 14 shows a sample analysis replacing 10% of commutes with PHEVs, using the "uncontrolled charging" scenario.

Table 14. Sample analysis, uncontrolled charging, one year, 20% commute replacement

County	NetCO_2 (MT)	NetNO_x (MT)	NetSO_2 (MT)
1	2087.48	19.49	54.12
3	-31229.06	-10.53	38.94
5	-24133.20	-9.02	30.14
7	-14661.21	5.29	48.98
9	455.04	6.16	17.10
11	1007.27	9.73	27.03
13	-21730.02	-7.88	26.28
15	-2292.87	18.22	58.84
17	-12068.42	-4.02	14.88
19	-11521.06	-11.56	0.11
21	-20793.44	-8.87	17.10
23	-42966.82	-29.13	24.84
25	-40643.20	-41.20	0.40
27	-32871.22	-35.92	0.35
29	-31275.27	-25.75	16.24
31	-15555.02	-0.66	32.10
33	582.92	5.26	14.59
35	-22614.22	-14.38	15.43
37	-16519.49	-15.83	0.15
39	-21873.61	-9.74	23.07
41	-8888.62	-8.41	0.08
Total	-367504.00	-168.77	460.76

Overall, CO_2 emissions are reduced by over 367,000 metric tons annually in this scenario, NO_x emissions are reduced by 169 metric tons, and SO_x emissions increase by 461 metric tons. However, some counties experience an increase in nitrogen oxide emissions when a relatively large amount of electricity is generated in a particular county compared to the amount of vehicle traffic in that county.

Effect on gas tax per county

Vehicle miles can be separated into electric miles and gasoline-powered miles. The effect on gasoline tax for a specific scenario in a particular county may be determined by calculating the gallons of gasoline that would be required to drive the number of all-electric miles produced in the scenario. Once these replaced gallons are found, the loss in gasoline tax revenue may be found by multiplying by the amount of money per gallon a county receives in tax. Table 15 shows the impact the lost gasoline will have on state and federal gasoline tax in the previously described scenario.

Table 15. Impact on Gasoline Tax Revenue from Sample Simulation

County	Gas Replaced (gallons)	State Tax Lost	Federal Tax Lost	Total Tax Lost
1	8208.7	$ 1,190.30	$ 1,510.40	$ 2,700.70
3	23226	$ 3,367.80	$ 4,273.60	$ 7,641.40
5	18347	$ 2,660.30	$ 3,375.80	$ 6,036.10
7	16187	$ 2,347.10	$ 2,978.40	$ 5,325.50
9	2702.8	$ 391.91	$ 497.31	$ 889.22
11	4118.6	$ 597.19	$ 757.82	$ 1,355.01
13	16062	$ 2,329.00	$ 2,955.40	$ 5,284.40
15	11344	$ 1,644.80	$ 2,087.20	$ 3,732.00
17	8947.2	$ 1,297.30	$ 1,646.30	$ 2,943.60
19	6751	$ 978.89	$ 1,242.20	$ 2,221.09
21	14200	$ 2,059.10	$ 2,612.90	$ 4,672.00
23	28250	$ 4,096.30	$ 5,198.10	$ 9,294.40
25	23836	$ 3,456.20	$ 4,385.70	$ 7,841.90
27	19405	$ 2,813.80	$ 3,570.60	$ 6,384.40
29	21079	$ 3,056.40	$ 3,878.50	$ 6,934.90
31	13759	$ 1,995.00	$ 2,531.60	$ 4,526.60
33	2203.1	$ 319.44	$ 405.36	$ 724.80
35	15185	$ 2,201.90	$ 2,794.10	$ 4,996.00
37	9642.9	$ 1,398.20	$ 1,774.30	$ 3,172.50
39	15736	$ 2,281.80	$ 2,895.50	$ 5,177.30
41	5183.4	$ 751.59	$ 953.74	$ 1,705.34
Total	284373.7	$ 41,234.32	$ 52,324.84	$ 93,559.16

SUMMARY AND CONCLUSIONS

A model was developed to analyze the impact of replacing X% of conventional vehicle commutes originating within a specific New Jersey county with commutes by plug-in hybrid electric vehicles. Commute distributions are created for each county and used to evaluate the impact per county on various vehicle tailpipe emissions as well as emissions from electric generation. Displaced gasoline may be used to evaluate the impact of this replacement on county revenue from gasoline tax.

It is important to consider all tradeoffs when analyzing the implementation of PHEVs. In all cases, a reduction in gasoline combustion results in lower carbon dioxide and other vehicle tailpipe emissions, such as carbon monoxide, hydrocarbons, and non-methane organic gasses. However, added demand on the electric grid results in increased sulfur dioxide emissions. While net nitrogen oxides emissions in the state are shown to decrease in the model, depending on the number of vehicle miles driven and what particular point sources are in a given county, NO_X emissions may increase in that county.

In the aforementioned sample simulation, the reduction of 367,000 metric tons of CO_2 represents a 0.3% reduction in New Jersey yearly carbon dioxide emissions (99 million tonnes). In this scenario, New Jersey annual NO_X emissions (169,000 tonnes) are decreased by 0.1%, and annual SO_X emissions (16,000 tonnes) increase by 2.8%[45].

Local policy will influence the adoption of PHEV in New Jersey. For example: implementation of smart grid technology to allow demand-based pricing of electricity, rebates to facilitate the installation of recharging stations, and gasoline tax rates will all affect consumer demand for PHEV's. We anticipate this model will be a useful tool for policy makers to determine appropriate initiatives to maximize the potential benefits of PHEV's. As the case study suggests, there are tradeoffs to environmental policy that might not be apparent through a first order analysis.

APPENDIX A: DISPATCHABLE UTILITY PLANTS IN NEW JERSEY

Table 8. Typical Dispatchable Plants Location and Emissions Rates, by Utility Service Provider[32]

Plant Name	County	NO_X (lb/kWhr)	SO_2 (lb/kWhr)	CO_2 Equiv (lb/kWhr)
Atlantic City Electric				
B L England	Cape May	0.0045095	0.0065667	2.2512559
Deepwater	Salem	0.0039985	0.0076434	1.9655097
Logan Generating Company LP	Gloucester	0.0012089	0.0011952	1.9393997
Jersey Central Power & Light Co				
AES Red Oak LLC	Middlesex	0.0000769	0.0000044	0.8684845
Asbury Park Press	Monmouth	0.0015329	0.0000185	0.6637196
Aventis Pharmaceuticals	Somerset	0.000511	0.0000203	0.6485461
MARS Chocolate North American LLC	Warren	0.0005243	0.0000324	1.1154827
NAEA Lakewood LLC	Ocean	0.0002275	0.0000086	0.9669317
NEO Freehold Gen LLC	Monmouth	0.0020822	0.0000244	0.8990217
Sayreville Cogeneration Facility	Middlesex	0.0007326	0.0000051	1.0123258
PSEG				
Bayonne Plant Holding LLC	Hudson	0.0001658	0.000003	0.5982608
Bergen Generating Station	Bergen	0.0001531	0.0000048	0.9220824
Bristol Myers Squibb	Middlesex	0.0005082	0.0000211	0.6438172
Camden Plant Holding LLC	Camden	0.0003131	0.0000053	1.0586982
Hoffmann LaRoche	Passaic	0.0004952	0.0000188	0.6298621
Kenilworth Energy Facility	Union	0.0008926	0.0000251	0.8597712
Merck Rahway Power Plant	Union	0.0000643	0.000021	0.658022
PSEG Burlington Generating Station	Burlington	0.0014072	0.0001674	1.191814
PSEG Hudson Generating Station[G]	Hudson	0.000483	0.000177	0.775782
PSEG Linden Generating Station	Union	0.0000731	0.0000047	0.8776163
PSEG Mercer Generating Station	Mercer	0.0009573	0.0091868	2.299602
Trigen Trenton Energy	Mercer	0.0031928	0.0002454	0.7381153
University of Medicine Dentistry NJ	Essex	0.000553	0.0000211	0.7026374

[G] As Hudson Generating Station received a significant emissions overhaul in 2010 shortly after eGRID information was published, new emissions rates were calculated using 2014 data.

Table 9. Peaking Dispatchable Plants Location and Emissions Rates, by Utility Service Provider[32]

Atlantic City Electric				
Plant Name	**County**	**NO_X (lb/kWhr)**	**SO_2 (lb/kWhr)**	**CO_2 Equiv (lb/kWhr)**
Cumberland	Cumberland	0.0008573	0.000017	1.3019405
Jersey Central Power & Light Co				
Forked River	Ocean	0.0019398	0.0003671	1.7268699
NAEA Ocean Peaking Power LLC	Ocean	0.0003397	0.0000065	1.2823576
Parlin Power Plant	Middlesex	0.00052	0.0000059	1.1788502
PSEG				
Elmwood Energy Holdings LLC	Bergen	0.0005773	0.0000062	1.2268081
Haworth Water Treatment Plant	Bergen	0.0029381	0.0000375	1.2685799
PSEG Edison Generating Station	Middlesex	0.0034042	0.0001258	1.8123205
PSEG Essex Generating Station	Essex	0.0060054	0.0001249	1.7204911
PSEG Kearny Generating Station	Hudson	0.001436	0.0000092	1.2021251
PSEG Sewaren Generating Station	Middlesex	0.0015813	0.0008262	1.9362018

APPENDIX B: 2010 NEW JERSEY ELECTRICAL LOAD PJM DATA APPROXIMATION

The data acquired from PJM is organized by their service regions. The Mid-Atlantic Region services New Jersey, Delaware, Pennsylvania, and Maryland. A map of the PJM territory by service region is shown in Figure 16.

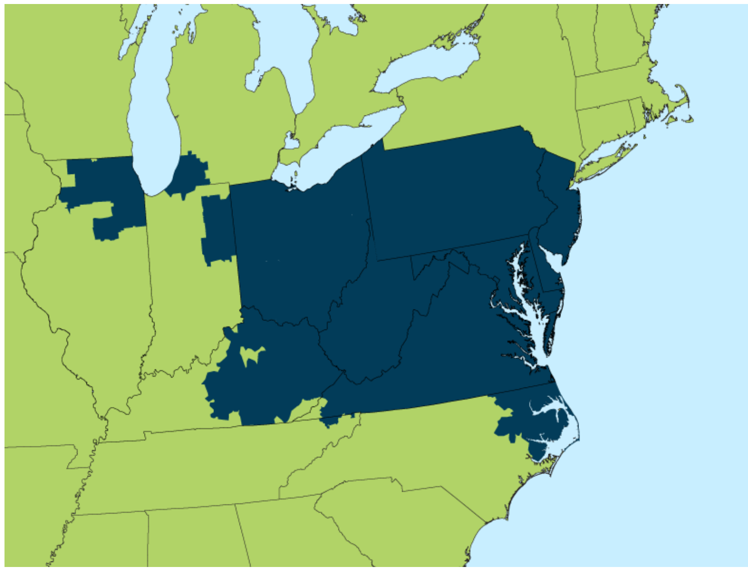

Figure 16. PJM Mid-Atlantic Region[47]

Data from PJM are organized by service region. Therefore, the electrical usage of New Jersey must be estimated from the total Mid-Atlantic usage. An assumption was made that the electric distribution throughout the Mid Atlantic Region scales with population. This assumption suggests that the electric usage in New Jersey is the ratio of the population on New Jersey to the population of the entire Mid-Atlantic region times the electric usage in all of the Mid-Atlantic region. The PJM map in Figure 16 was compared to state maps to identify counties in New Jersey, Pennsylvania, Delaware and Maryland that are not serviced by PJM. State and County populations were then obtained from US census data[49]. The resulting counties and populations are listed in

Table through Table 16 for Pennsylvania, Maryland, and New Jersey, respectively. Note that all of Delaware is serviced by PJM. Next, the population living in the Mid Atlantic Region was estimated by subtracting the populations of counties that are not contained in the Mid Atlantic Region, but are contained in an included state from their state's population. These calculations are summarized in Table 8.

Table 10. Population of counties in Pennsylvania that are not serviced by PJM.

County	Population
Centre	153 990
Potter	17 457
Tioga	41 981
Cameron	5 085
Elk	31 946
Franklin	14 845
Fulton	149 618
Bedford	49 762
Mercer	116 638
Butler	183 862
Lawrence	91 108
Beaver	170 245
Allegheny	1 223 348
Washington	207 820
Greene	38 686
Fayette	136 606
Westmoreland	365 169
Indiana	13 975
Armstrong	68 941
Clarion	39 988
Frederick	45 200
Total	9 607 531

Table 11. Populations of Counties in Maryland that are not serviced by PJM

County	Population
Garnet	30 097
Allegany	75 087
Washington	147 430
Frederick	233 385
Total	485 999

Table 16. Populations of counties in New Jersey that are not serviced by PJM.

County	Population
Passaic	501 226
Total	501 226

Table 13. Total population and population serviced by PJM of states in PJM territory.

State	Total Population	Excluded Population	Population Serviced by PJM
Delaware	897 934	0	897 934
Maryland	5 773 552	485 999	5 287 553
New Jersey	8 791 894	501 226	8 290 668
Pennsylvania	12 773 801	3 166 270	9 607 531
Total	28 237 181	4 153 495	24 083 686

APPENDIX C: FUEL FOR DISPATCHABLE AND NONDISPATCHABLE PLANTS

Table 14. Dispatchable Power Plants and their Fuel Costs

Plant	Primary Fuel	Fuel Cost ($/kWh)
Logan Generating Company LP	COAL	0.02128
Deepwater	COAL	0.02346
B L England	COAL	0.02488
PSEG Hudson Generating Station	COAL	0.02493
PSEG Mercer Generating Station	COAL	0.02537
Bayonne Plant Holding LLC	GAS	0.02559
Hoffmann LaRoche	GAS	0.02740
Bristol Myers Squibb	GAS	0.02797
Aventis Pharmaceuticals	GAS	0.02820
Merck Rahway Power Plant	GAS	0.02858
Asbury Park Press	GAS	0.02879
Trigen Trenton Energy	GAS	0.02902
University of Medicine Dentistry NJ	GAS	0.03056
AES Red Oak LLC	GAS	0.03715
Kenilworth Energy Facility	GAS	0.03740
PSEG Linden Generating Station	GAS	0.03751
NEO Freehold Gen LLC	GAS	0.03911
Bergen Generating Station	GAS	0.03943
NAEA Lakewood LLC	GAS	0.04116
Sayreville Cogeneration Facility	GAS	0.04331
Camden Plant Holding LLC	GAS	0.04529

MARS Chocolate North American LLC	GAS	0.04852
PSEG Burlington Generating Station	GAS	0.04879
Parlin Power Plant	GAS	0.05043
PSEG Kearny Generating Station	GAS	0.05063
Elmwood Energy Holdings LLC	GAS	0.05248
NAEA Ocean Peaking Power LLC	GAS	0.05486
Cumberland	GAS	0.05498
Haworth Water Treatment Plant	GAS	0.05518
Forked River	GAS	0.07104
PSEG Essex Generating Station	GAS	0.07290
PSEG Edison Generating Station	GAS	0.07703
PSEG Sewaren Generating Station	GAS	0.08105

Table 15. Non-dispatchable plants and their fuel sources.

PSEG Salem Generating Station	NUCLEAR
PSEG Hope Creek Generating Station	NUCLEAR
Linden Cogen Plant	GAS
Oyster Creek	NUCLEAR
Chambers Cogeneration LP	COAL
Covanta Essex Company	BIOMASS
Paulsboro Refinery	GAS
Newark Bay Cogeneration Partnership LP	GAS
Union County Resource Recovery	BIOMASS
Pedricktown Cogeneration Company LP	GAS
Camden Resource Recovery Facility	BIOMASS
Eagle Point Cogeneration	GAS
Bayway Refinery	OIL
Wheelabrator Gloucester LP	BIOMASS
Covanta Warren Energy	BIOMASS

APPENDIX D: DATA VALIDATION

Commuter Trips

Commuter trip information obtained from CCTP 5-year data (2006-2010)[31] used in the model was compared to commuter data from Delaware Valley Regional Planning Commission's (DVRPC) County-to-County Commuting Flows, 2006-2010[50]. While the DVRPC data do not include New Jersey counties not adjacent to DRPC region counties; namely Bergen, Essex, Hudson, Morris, Passaic, Sussex, and Union; they do account for both "other New Jersey counties" commute destinations, as well as "other states or Puerto Rico." Additionally, DVRPC data include trips to Delaware, Pennsylvania, and Maryland. According to AASHTO data, 95.5% of the commutes out of state that were not to Delaware, Pennsylvania, or Maryland were to New York State. Additionally, 92.5% of New Jersey commutes to New York State were to New York City.

The DVRPC data are not sorted by mode type, so adjustments were needed to exclude non-automobile trips. According to the American Community Survey[49], 72% of commutes in 2011-2013 were made by workers driving an automobile alone.

After adjusting the DVRPC data by these numbers, the number of trips leaving any given New Jersey county in the region tracked by DVRPC was compared. All values were within approximately 10%. The comparisons by county are shown in Table.

Table 16. Comparison of CCTP commute data to DVRPC

County	CCTP Totals	DVRPC Adjusted	Difference	%Diff
Atlantic	91561	90557	1004	1.10%
Burlington	173911	155793	18118	10.42%
Camden	177077	171344	5733	3.24%
Cape May	30657	31242	-585	-1.91%
Cumberland	47990	44460	3530	7.35%
Gloucester	106633	96731	9902	9.29%
Hunterdon	49621	44849	4772	9.62%
Mercer	119699	122506	-2807	-2.35%
Middlesex	278699	274610	4089	1.47%
Monmouth	219665	215720	3945	1.80%
Ocean	187453	170586	16867	9.00%
Salem	21456	19065	2391	11.15%
Somerset	124678	113854	10824	8.68%
Warren	37425	36450	975	2.61%
Total	1666525	1587766	78759	4.73%

Emissions

A sample simulation with 20% PHEV commute replacement and delayed charging scenario give a reduction of approximately 207,000 metric tons of CO_2 and a 1,600 metric ton increase in NO_x. These represent changes of -0.2% of total NJ CO_2 production in 2011 (99 million tonnes) and +1% of total NO_x production (169,000 tonnes)**Error! Reference source not found.**.

Transportation makes up for 41% of New Jersey CO_2 production, and electricity another 20%. According to the National Household Transportation Survey, commutes make up fewer than 30% of total vehicle miles travelled. Replacing 20% of 30% of the total conventional vehicle miles has a maximum possible reduction of 6% of yearly CO_2 production from transportation, and 2.46% of yearly total CO_2 production in the state from all sources. Because CO_2 is still generated from electricity used to charge PHEVs as well as emitted from PHEV tailpipes while operating in CS mode, it is expected that the actual difference would be less than this maximum reduction.

The aforementioned simulation resulted in 650 tonnes of SO_2 added in New Jersey. Because SO_2 is not emitted from vehicle tailpipes, this increase can be directly compared to totals from the electric sector. Electric generation from electric generation was 10,700 tonnes in 2011. This additional 650 tonnes represents about a 1% increase in SO_x production from the electric sector. The total energy used to charge PHEVs in the simulation was 2,356 MWh, which is 0.0037% of the state's 63 million MWh generated in 2011. This discrepancy can be explained by the use of marginal energy production for the purposes of attributing emissions to PHEV charging in the model. Because all of the electricity used to charge PHEVs in the model is from higher-polluting marginal and peaking power plants, the fraction of energy used to total NJ energy will be lower than the fraction of SO_x produced in the model to SO_x produced in the state annually.

APPENDIX E: ABATEMENT VALUE

There are many ways to evaluate the benefits of decreasing harmful emissions. Muller and Mendelsohn[53] suggests a method for determining marginal abatement value by county, and those values are used to calculate the following, as the model also attributes emissions at the county level. Because CO_2 cannot be attributed to individual counties, the average value per ton of CO_2 purchased by NJ in the cap and trade program, $2.34, will be used.

Because NO_x and SO_x are valued much higher than CO_2 per ton, the benefit according to the method outlined in Muller and Mendelsohn does not make up for the estimated loss in tax revenue. Table 14 shows the marginal abatement value per county by emission using this method. Note that this approach has not been adopted, and the values are shown only as an example of how this model could be utilized, and why a county level approach to emissions can be useful.

Table 17. Marginal Abatement Values from Sample Simulation

County	NetCO_2 (Tonnes)	NetNO_x (kg)	NetSO_2 (kg)	CO_2 Abatement	NO_x Abatement	SO_2 Abatement
1	-12.702	37.887	104.93	$32.7629	$(31.21)	$(184.12)
3	-115.17	-84.538	94.755	$297.0654	$(25.57)	$(227.28)
5	-92.265	-51.938	68.508	$237.9889	$(11.54)	$(152.38)
7	-65.246	-21.933	104.64	$168.2969	$1.03	$(214.29)
9	-4.9873	11.968	33.147	$12.8642	$(9.68)	$(58.16)
11	-6.5119	18.922	52.405	$16.7968	$(14.66)	$(91.95)
13	-79.839	-58.613	63.929	$205.9383	$(55.55)	$(153.34)
15	-29.509	27.662	116.42	$76.1165	$(15.15)	$(211.66)
17	-44.655	-32.297	36.2	$115.1839	$(38.29)	$(86.83)
19	-39.811	-23.643	0.115262	$102.6897	$(19.35)	$(0.33)
21	-78.808	-45.727	41.547	$203.2773	$(23.35)	$(99.67)
23	-154.15	-99.395	60.123	$397.6167	$(100.27)	$(144.32)
25	-139.91	-84.238	0.410678	$360.8835	$(71.63)	$(1.19)
27	-109.75	-73.445	0.358058	$283.0958	$(83.35)	$(1.04)
29	-114.61	-53.233	31.218	$295.6297	$(59.49)	$(55.13)
31	-62.703	-33.171	71.82	$161.7358	$(46.18)	$(156.39)
33	-3.3303	10.218	28.298	$8.5903	$(5.97)	$(49.65)
35	-81.162	-54.209	37.413	$209.3511	$(67.02)	$(89.79)
37	-58.071	-32.358	0.157752	$149.7897	$(31.63)	$(0.46)
39	-79.753	-57.179	56.089	$205.71	$(63.27)	$(134.55)
41	-31.385	-17.195	0.083828	$80.95	$(15.02)	$(0.243)
Total	-1404.33	-716.455	1002.568	$3622.34	$(787.24)	$(2112.84)

APPENDIX F: MATHEMATICAL MODEL OUTLINE

An overview of the mathematical model used to analyze the impact of PHEV implementation follows. Inputs and outputs to the model will be elucidated. Algorithms used in calculating will also be explained.

Inputs

Due to the necessary repetitive capabilities of the model, timely needed data manipulation was performed prior to model calculation. The model requires specific matrices each with a different function. These matrices were created using a combination of excel and MATLAB scripts. Below is the 6 needed matrices, a description of each, and each of its own inputs and outputs.

<u>MilesMat(Origin County, Destination County, Origin Municipality, Destination Municipality)= Miles</u>

MilesMAT is a 4D matrix that holds a value for each county to county, municipality to municipality combination. The value is a representation of the distance, in miles, to make the trip from origin county, origin municipality, to destination county, destination municipality. All counties and municipalities were given a numerical nomenclature scheme.

<u>TripsMat(Origin County, Destination County, Origin Municipality, Destination Municipality) = # of Trips</u>

TripsMAT is a 4D matrix that holds a value for each county to county, municipality to municipality combination. The value is a representation of the number of commuters that make the trip from origin county, origin municipality, to destination county, destination municipality in one day. All counties and municipalities were given a numerical nomenclature scheme.

<u>DistBin(Origin County, Destination County, Bin Number) = # of Trips</u>

DistBin is a 3D matrix holding the number of commutes from origin county to destination county within a predetermined distance. Bin number increases with 5 mile intervals. All counties were given a numerical nomenclature scheme.

For example Bin number 1 = all trips 0-5 miles, 2 = all trips 5-10 miles, 3 = all 10-15 miles, etc...

<u>County Routes(Origin County, Destination County) = {Origin County, A, B,...N, Destination County}</u>

CountyRoutes is a 2D matrix where each value contains a cell of numbers signifying the counties necessary to cross if one was going to commute from origin county to destination county. The cell always starts at origin county and ends at destination county. All counties in-between are counties that would be essential to travel through if a commute spanned across multiple counties. All counties were given a numerical nomenclature scheme.

<u>County_E_Dist(County, NJ Electrical Distributor) = %</u>

County_E_Dist is a 2D matrix which reveals the percentage of the electrical distributor that provides service to the county in question. Each NJ electrical distributor was given a numerical representative value much like the counties. Percentages were determined by observing the portion of the population serviced by each distributor.

EDist(Electrical Distributor, Load Condition, County, Emissions Type) = lbs of emissions per KWHr

EDist is a 4D matrix that holds emissions rates for specific power plants. When fed the desired electrical distributor and load condition (referring to peak or off peak demand) , EDist can report back the amount of pounds of pollutants per KWHr for each county in NJ. EDist has the ability to report on all monitored pollutants, specifically, NOx, SOx, and CO2.

In addition to the above necessary matrices, the model requires some parameter inputs. These inputs were built in for model flexibility and iteration friendliness. Below are the 7 model variable inputs.

Table 18. Summary of Model Variable Input

Input Name	Variable Ranges	Description
Charge Scenario	1,2,3	Referring to the desired expected charging situation to which commuters will be electrically refueling their cars. 1 = at home at night 2 = at home at 6:00pm 3 = at day at work and home at night
Season	1,2,3,4	Referring to the season of the year: 1 = fall 2 = winter 3 = spring 4 = summer
Origin County	1 - 41 (negative integers)	The county to which the model will be replacing convention gas vehicle commutes with PHEV commutes
Number of Hybrids	0-1 (a fraction)	Fraction of conventional gas vehicle Commutes being replaced by PHEV commutes
MPG Gas	Any realistic number	MPG of conventional gas vehicle being replaced by PHEV's
MPG PHEV	Any realistic number	MPG of PHEV replacing conventional gas vehicles post PHEV battery depletion
Range	Any realistic number	Hybrid range on electric (Miles)

Model Algorithm

Gas Emissions Calculations

With all the inputs and matrices loaded, the model begins calculating emissions. First the county in question, Origin County, is separated from DistBin, looking at only the county to county distributions from a single origin county. This 2D matrix is called commuteDist. From here the summation of commuteDist is taken to get the total number of trips from origin county to every other county in NJ. This summation is then summed again to retrieve the total number of trips from Origin County. Each of the original summations is divided by the total (second summation) to get a percentage of commutes from origin county to each of the other counties in NJ. Using these percentages, and the commute distributions held in commutedist, a total number of miles driven from origin county to each other county in NJ is able to be calculated. Using the variables Range and Number of Hybrids, it is determined which of these miles would be classified conventional gas miles, PHEV electric miles, and PHEV gas miles.

Now with the three different mile measurements from origin county to each other county in NJ, miles are dispersed to in-between counties as necessary using matrix County Routes. From here known emissions constants are implemented based on MPG of each of the allocated vehicles (PHEV or conventional gas). Total emissions generated is calculated and stored for each county in NJ.

<u>Electrical Distribution</u>

To begin the electrical emissions analysis, a binary peak loading decision is made. Peak loading refers to the time when electrical distribution companies require the additional of dispatchable plants to meet the needs of the public and prevent brown outs. Peak loading only occurs in the summer during the day. It is for this reason peak loading conditions are only considered when charge scenario = 2 or 3 and season = 4.

For charge scenario 1 or 2, all representative PHEV owners will charge at home and thus all additional electrical generation will be through the specified origin county. Total electric miles, calculated in the Gas Emissions analysis, is used to calculate a corresponding KWHr measurement needed to drive those electric miles. Of these total KWHrs, each will be assigned to its designated electrical distribution company using the percentages found in County_E_Dist. From here, given the electrical distribution company and load condition, EDist is used to allocate the emissions created in each county due to the added electrical generation created by the PHEV addition. In the event of charge scenario 3, the process is iterated for half of all electric miles for each county in NJ. These miles contribute to electric draw at the destination county, not origin county. This is because commuters charging at work may be in a different county and the electricity used to recharge the PHEV could be coming from a different electric distributor. The other half of the electric miles are calculated for origin county due to charging at home *and* at work.

Outputs

The model calculates CO_2, NO_x, and SO_2 emissions generated in every county in NJ due to generating electricity equivalent to charging a number of PHEVs to travel the replaced miles. For gasoline emissions, including PHEVs driving in charge-sustaining mode, the model calculates emissions for every county for CO_2, NO_x, CO, HCHO, NMOG, and $PM_{2.5}$. It is worth noting that by default the $PM_{2.5}$ gasoline emissions rate is 0, under the assumption that vehicles being replaced by PHEVs are not significantly old, but this value may be changed if desired.

Currently, the model also outputs total KWHr of additional electricity generated, vehicle miles travelled in each mode and in total, total gasoline used in gallons, and totals for each emission tracked. A frontend is currently being developed that would allow a user to change inputs as desired in a user interface, and output selected charts and maps directly from the model interface.

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