Modeled Health Impacts of Changes in Transportation-Related Fine Particulate Matter Emissions Resulting From Proposed Climate Policy in Oregon

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Abstract

The focus of this research was to compare how different climate mitigation policies influence air pollutant emissions in the transportation sector. As these policies also often reduce other air pollutants harmful to humans, policies that mitigate greenhouse gases can lead to improved air quality and better health. (West et al., 2013). One such pollutant is fine particulate matter (PM 2.5), which, when inhaled deep into the lungs, can agitate asthma, as well as respiratory and heart conditions (Oregon Health Authority [OHA], 2017). Understanding the relationships and potential co-benefits of reducing air pollution through climate mitigation policies allows decision makers to assess the broader benefits of a specific policy.

My research examined climate policy scenarios based on proposed or current policy in Oregon. As a case study, emissions from passenger vehicles and light duty trucks were modeled for six different policy scenarios and one reference scenario for Jackson County, Oregon. The policy scenarios include several economy-wide carbon pricing policies, a transportation-specific zero-emission vehicle (ZEV) adoption scenario and a vehicle mile travel (VMT) tax policy.

Two separate models were utilized to develop the emissions estimates. The first was the Regional Strategic Planning Model (RSPM), used to model the impacts of different policies on the transportation sector. Select outputs from RSPM were used as inputs into EPA's Motor Vehicle Emissions Simulator (MOVES). MOVES produced estimates of greenhouse gas and particulate matter emissions for each scenario. These

results were compared to the reference scenario to determine the change in emissions. Based on this information, an economic analysis was constructed for comparison. The analysis included the monetized health benefits of emission reductions, social cost of carbon savings and, if applicable, revenue generation from pricing carbon.

The results demonstrated that, while high carbon-pricing scenarios have a greater impact on emissions, an increased adoption of zero-emission vehicles has similar impacts to a low to mid-range carbon price in regards. The zero-emission vehicle adoption policy resulted in 90% of the cumulative greenhouse gas emission reductions achieved by the high carbon-pricing scenario. The medium pricing scenario achieved only 52%. The reductions in PM 2.5 achieved by the zero-emission vehicle adoption scenario were less robust. The zero-emission vehicle policy resulted in 23% of the PM 2.5 emission reductions achieved by the high pricing scenario, slightly below the 26% achieved by the low pricing scenario.

The less robust reductions of PM 2.5 from the zero-emission vehicle scenario are a result of the shift in the source of PM 2.5 emissions. Engine exhaust is the primary source of PM 2.5 emissions in the initial years, while tire wear and brake use are greater contributors in future years. For example, 84% of PM 2.5 emissions were attributed to exhaust in 2010 while only 24% of PM 2.5 emissions were attributable to exhaust in 2050, the other portion being emissions from tire and break wear.

With this in mind, policies that reduce exhaust emissions have greater co-benefits in the near term than in future years, when engine technology advances reduce emissions exhaust. Alternatively, in future years, reductions in VMT have a greater impact on PM 2.5 emissions since emissions are primarily resulting from tire wear and break use.

Dedication

This work is dedicated to my husband, Simeon Realov, and my parents, Ted and Jennifer Elbel, for believing in the value of education and inspiring me to always continue learning. To my son, Teddy, I'm looking forward to a lifetime of learning with you.

Acknowledgments

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Chapter I

Introduction

Human-caused greenhouse gas emissions are influencing our climate and the impact can be detected in the warming of our atmosphere and oceans (Intergovernmental Panel on Climate Change [IPCC], 2014). The primary source of these emissions comes from the combustion of fossil fuels used to power our buildings, heat our homes, and power our vehicles. In the United States, the transportation sector generated the largest share of greenhouse gas emissions in 2016, surpassing national emissions from electricity production for the first time (U.S. Environmental Protection Agency [EPA], 2018a). The greatest contributors to emissions within the transportation sector are passenger cars and light duty trucks (EPA, 2018a).

In the Pacific Northwest, the primary source of electricity is non-greenhouse gas emitting hydropower. Because Oregon's electricity mix is relatively clean, emissions from the transportation sector are the greatest source of annual greenhouse gas emissions in the state (Oregon Department of Environmental Quality [DEQ], 2018). Oregon has legislative goals is to reduce statewide greenhouse gas emissions to 10% below 1990 levels by 2020 and 75% below 1990 levels by 2050 (DEQ, 2018). Data produced by the Oregon DEQ indicates that Oregon is not on track to meet these goals (Figure 1). To correct its current trajectory, Oregon must implement comprehensive climate mitigation policy and must address emissions in the largest emitting sector, transportation.

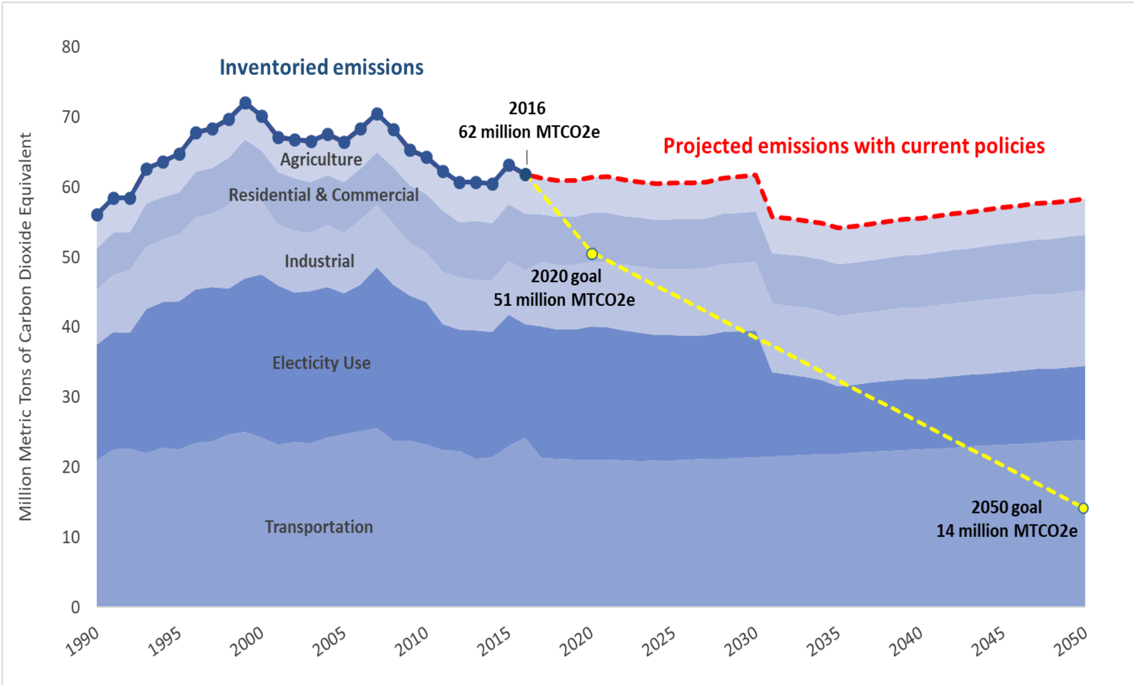


Figure 1. Oregon greenhouse gas emissions and targets. (DEQ, 2018).

Oregon has adopted several policies and implemented several others that mitigate emissions in multiple sectors. These include a renewable portfolio standard, energy efficiency programs, a Clean Fuels Program, adopting California's Low-Emission Vehicle (LEV) Standards and Zero Emission Vehicle (ZEV) program, providing electric vehicle rebates, and, having a requirement that coal be removed from utility portfolios for the largest utilities by 2035 (Oregon Department of Energy [ODOE], 2018). Even with these measures in place, Oregon is not projected to meet its 2020 or 2050 goals (Figure 1).

With the exception of the Clean Fuels Program and electric vehicle incentives, Oregon has implemented minimal state policy that would specifically reduce emissions in the transportation sector. However, additional policy actions at the state level have been proposed including pricing emissions through either a carbon tax or a cap and trade program. Other mitigation options – increasing the adoption of electric vehicles, implementing vehicle miles traveled (VMT) taxes, and improving infrastructure and land use planning – also have been explored, but not broadly implemented. Mitigation strategies that both increase the greenhouse gas emission reduction potential and decrease the negative economic impact of these policies are actively being studied to inform decision makers on the next steps Oregon must take to reach its greenhouse gas reduction goals.

Implementing greenhouse gas mitigation policies can lead to improved air quality because these policies often reduce other air pollutants (West et al., 2013). Oregon air quality suffers from high concentrations of fine particulate matter (PM 2.5), with three Oregon counties exceeding the National Ambient Air Quality Standards (NAAQS) in 2013 (Oregon Health Authority [OHA], 2017). Primary sources of PM 2.5 come from wood stoves, motor vehicles, factories, and construction (OHA, 2017). When inhaled deep into the lungs, fine particulate matter can agitate asthma, heart disease, the respiratory system, and heart conditions (OHA, 2017). Because emissions from motor vehicles are the largest contributor to greenhouse gas emissions and a major contributor to fine particulate matter, policies that mitigate greenhouse gases in the transportation sector benefit air quality by reducing the emission of localized fine particulates.

While state-specific assessments on the greenhouse gas emissions benefits and economic impacts of these policies and programs have been studied, they have not consistently evaluated the co-benefits of improvements to air quality. Analysis of the co-benefits to air quality and health provide important, additional information for consideration when designing greenhouse gas policy options, especially at the local level.

These evaluations may indicate additional societal and economic benefits not incorporated or fully addressed in previous studies focused on the greenhouse gas emissions and direct economic impacts.

Research Significance and Objectives

This thesis assesses changes in primary fine particulate matter (PM 2.5) emissions as a potential co-benefit of proposed carbon mitigation policy in Oregon. The assessment focused on passenger car and light truck emissions in a community experiencing air quality concerns, the Rogue Valley Metropolitan Planning Organization (RVMPO) area, in Jackson County. Modeled emissions for Jackson County were compared against a baseline scenario for the potential reduction of primary fine particulate matter and greenhouse gas emissions resulting from the impact of several proposed statewide greenhouse gas mitigation polices. Furthering the assessment, the modeled particulate matter emissions from each scenario were used to monetize the health impacts based on those modeled emissions. The monetized impacts were used in an economic benefit analysis to compare the scenarios.

The results of this research produced regional-specific data that allow for a more comprehensive comparison of the greenhouse gas mitigation policy options and potential co-benefits.

The objectives of my research were:

- To model and compare changes in transportation-related greenhouse gas and particulate matter emissions resulting from different climate policy scenarios.

- To evaluate potential health benefits of transportation sector climate mitigation policy.
- To design and test a viable and repeatable pathway to translate modeled emissions in the transportation sector into health impacts and monetize those impacts as inputs into an economic analysis.
- To allow for a more comprehensive analysis of the impact of climate policy in Oregon by analyzing data that is both specific and valuable to Oregon stakeholders.

Background

Policy that mitigates greenhouse gas emissions also often reduces co-emitted air pollutants, creating benefits not only for the climate but also for human health (West et al., 2013). Past studies have estimated that monetization of these benefits to human health are substantial, creating a strong argument for their inclusion in an economic analysis of the costs and benefits of a mitigation policy (West et al., 2013). For example, an analysis of U.S. Power Plan Carbon Standards estimated that the health co-benefits of the standards would exceed program costs by $12 billion per year. When the Social Cost of Carbon (SCC) was included, the net benefits increased to $33 billion per year (Buonocore et al., 2016). Similar benefits can be assessed in the transportation sector. An analysis of California's low carbon fuel and cap and trade program estimated that, combined, these programs would result in $8.3 billion in savings by 2025 due to reductions in health costs associated with air pollution (O'Conner et al., 2014).

PM 2.5 Air Pollution and Health

There is an established link between air pollution and mortality and morbidity. This link is strongly associated with the presence of particulate matter (Dockery et al., 1993). Fine particulate matter, if inhaled, is capable of reaching the lower lung, an area of the body that has little ability to clear such matter (Fraser, 2011). Once in the body, particulate matter is linked to breathing difficulties, decreased lung function, asthma, pulmonary disease, cardiovascular disease, cancer, and premature death (Fraser, 2011).

Combustion is a major source of particulate matter, including combustion of coal and fossil fuel used in mobile transportation (Laden, Neas, Dockery, & Schwartz, 2000). However, research indicates that there is a greater cardiovascular response to traffic-related particulate matter than to coal (Laden et al., 2000). There is also an established linear relationship between particulate matter from transportation and daily deaths (Schwartz, Laden, & Zanobetti, 2002). Therefore, increases in fine particulate matter are detrimental to health, while decreases in transportation-related particulate matter result in reductions of mortality and morbidity related to poor air quality (Laden, Schwartz, Speizer, & Dockery, 2006).

Vehicles emit primary PM 2.5 emissions from their exhaust, tires and brakes. Exhaust emissions are related to engine operation and are emitted through the tailpipe of a vehicle (EPA, 2015). Tire and brake emissions are produced from the friction or wear and use of those components of a vehicle. The level of emissions from these sources are impacted by other factors, such as vehicle weight, road type, speeds, congestion, and technology type. Over time, the proportion of tire and brake wear may increase as exhaust emissions decrease (Bai, Du, & Reid, 2015). Indirectly, PM 2.5 also can be associated with the generation of electricity used to power electric vehicles if the generating fuel type is combusted fossil fuels, such as coal or natural gas.

Climate Policy and Transportation

Climate mitigation policy can take different forms. Most take into account not only the end goal of the policy but also its cost-effectiveness, distributional equity, the ability to address uncertainties, and political feasibility (Goulder & Perry, 2008). Two of the main policy constructs are command-and-control models that set specific standards and economic incentives (including market-based mechanisms) that create financial incentives to achieve the desired result (EPA, 2018b). Other types of incentive policies also influence the transportation sector, including vehicle rebates or discounts in public transit. Whereas compliance under a command-and-control regulation is predetermined, the compliance scenario under each economic or incentive policy approach can vary due to the impact of economic influence, technological investments, and market systems. No single policy design is necessarily superior and each policy structure requires trade-offs (Goulder & Perry, 2008). In some instances, it may be advisable to take a hybrid approach that combines features. To avoid market-failures, for example, it may be necessary to implement multiple policies that complement one another (Goulder & Perry, 2008).

Economic incentive programs utilize different mechanisms to influence behavior by attaching a cost to pollution, such as greenhouse gas emissions, thereby pricing the externality. The relationship between pricing policies and emissions in the transportation sector are complex. Gasoline and diesel are considered inelastic goods, meaning that changes in the cost to consumers has little influence on demand (Morris, 2014).

Expenditures on transportation by households remain constant over time and changes to fuel prices do not have a large impact on the amount of fuel consumed or VMT (Gregor, 2015). This is a result of households shifting expenditures in other areas to accommodate increased fuel prices. Once a household runs out of options to shift expenditures, they may reduce fuel purchases and VMT (Gregor, 2015). Changes to costs in the short term are relatively small; however, increased costs over time have a greater influence, and there is evidence that sustained price signals influence VMT, fleet fuel economy, and mass transit use (Brand, 2009).

VMT taxes operate differently than pricing emissions. While a carbon tax or a cap and trade program operate by attaching costs to fuel consumed, a VMT tax attaches costs to actual distance traveled. A basic VMT tax may encourage less use of a vehicle, but it does not support the transition to more fuel-efficient vehicles (O'Rear, Sarica, & Tyner, 2015).

Oregon's Greenhouse Gas Policy Options

When greenhouse gas mitigation pricing policy is designed effectively, pricing the carbon externality achieves the desired emission reductions for the least cost method of abatement (EPA, 2018b). To mitigate emissions in Oregon, decision makers have proposed several economic approaches. The economic and incentive policies under consideration include an overall tax on carbon, most recently Senate Bill 306 (2013), and variations of a cap and trade program proposed during the 2019 legislative session, House Bill 2020 (2019). In 2019, Oregon also implemented SB1044 (2019), which includes goals to increase the number of zero-emission vehicles (ZEV) registered and operating in the state.

Oregon has also considered policy actions in the transportation sector that allow for adaptation to changes resulting from mitigation policy. One policy that has been piloted in Oregon is shifting the revenue-generating source for transportation infrastructure from a fuel tax to a VMT tax. The proposed policy approaches are discussed in more detail below.

Carbon tax. A carbon tax places a price, typically in dollars per metric ton, on greenhouse gas emissions to price the negative externality in all sectors (Liu et al., 2014). In 2013 Oregon legislatures passed Senate Bill 306, which commissioned a study on a statewide carbon tax (Liu et al., 2014). The study reviewed the Oregon specific greenhouse gas emissions and economic response to several different carbon tax prices ranging from $10 to $150 per ton of emissions. Like other economic policies, the carbon tax changes the demand for transportation fuels by changing the price of those fuels. The amount of emission reduction depends on consumer response to the tax rate (Liu et al., 2014). A carbon tax establishes a predetermined price on greenhouse gas emissions but allows the market to determine the response to that price, so unlike a cap and trade program, there is not a guaranteed amount of emission reductions (Liu et al., 2014). The study estimated that a $10 per ton tax on emissions would result in an increase of $0.10 per gallon of fuel (Liu et al., 2014). Researchers reviewed the impact to jobs and the economy but did not consider the air quality benefits. The primary scenario assessed was a $10 per ton tax that increased by $10 annually with a maximum price of $60 per ton (Liu & Renfro, 2013).

Cap and trade. In 2019, Oregon introduced HB 2020, which was cap and trade legislation modeled after California's program. This bill proposed a multi-sector cap on greenhouse gas emissions that would gradually decline over time. If implemented, this policy would create a compliance obligation for all greenhouse gas emissions covered under the scope of the program including emissions from industry, natural gas use, electricity generation and transportation fuels (SB 2020, 2019). Covered entities would need to reduce emissions or purchase allowances to meet emission reduction goals and the number of allowances would decrease over time (SB 2020, 2019). Unlike a carbon tax, a cap and trade program proscribes a guaranteed amount of emission reductions, but it does not dictate where those reductions must occur and allows the price of compliance to fluctuate (Liu et al, 2013). The policy would result in an 80% reduction in greenhouse gas emissions from 1990 levels by 2050 (Rolans-Holst, Evans, Neal, & Behnke, 2018).

Within the transportation sector, fuel importers would be obligated to purchase allowances to comply with the cap and trade and would be directly regulated by the program. The transportation sector is also one of the few sources of emissions that would not receive any free allowances or rebates, as was proposed for other sectors like trade-exposed industrial facilities or electricity suppliers (SB 2020, 2019). While consumers would not directly purchase allowances for compliance, the costs are expected to be passed down from fuel importers to consumers. The cost of allowances would be factored into the cost for the fuel to consumers by the regulated party, the fuel importer

(Flachsland, Brunner, Edenhofer, & Creutzig, 2011). This is intended to create a price signal for consumers. As that price signal increases over time it is expected to impact fuel use and driving habits helping to achieve greenhouse gas emission reductions. However, under a cap and trade program, there is evidence that fuel prices are not radically affected by the price on carbon and that initially the costs would not exceed regular price fluctuations in fuel costs (Raborn, 2009). Additionally, since this is a multi-sector program, emission reductions in the transportation sector may be proportionally smaller than reductions in other sectors in the beginning of the program. While a cap and trade program may be appropriate for achieving least cost emissions reductions market wide, due to the inelasticity of fuel purchasing, this type of program may not be the most effective way of achieving immediate emissions reductions in the transportation sector (Raborn, 2009).

Under the HB 2020 proposal, it was assumed that Oregon would join the Western Climate Initiative, a non-profit that assists with emissions trading programs (Malik, 2019). An economic assessment completed by the Oregon Legislative Revenue Office modeled revenue impacts of the proposed policy. This analysis relied on an economic analysis completed by Berkeley Economic Analysis and Research (BEAR), that included three projected allowance price scenarios under the policy: a low, medium, and high projection (Roland-Holst, Evans, Neal & Behnke, 2018). While in most active cap and trade markets prices tend to stay close to the floor price, the legislative economic analysis used the medium pricing projection from the BEAR analysis listed in Table 1 (Malik, 2019). The legislative economic analysis did not include air quality benefits.

Table 1. HB 2020 carbon price scenarios.

	2021	2025	2030	2035	2040	2050
Low	$19.30	$25.6	$36.4	$51.7	$73.8	$151.2
Med	$22.90	$38.2	$72.5	$103.1	$147.0	$301.2
High	$72.20	$95.7	$135.8	$193.2	$275.5	$564.4

Low, medium, and high estimated allowance prices for HB 2020 cap and trade market. Dollar values displayed in 2019 dollars per metric ton of carbon dioxide equivalent (Roland-Holst et al., 2018).

VMT tax. Fuel taxes are sensitive to changes in the fuel efficiency of vehicles. In response to the potential loss of revenue resulting from reduced purchases of gasoline and diesel due to a higher adoption of more fuel-efficient and electric vehicles, Oregon has explored the use of an alternative to the fuel tax - a mileage-based tax program originally proposed in the 2013 regular legislative session in Senate Bill 810 (SB 810, 2013). The main purpose of this program was not to reduce emissions but to adapt and explore funding mechanisms to changes resulting from emissions reduction strategies, such as improved vehicle fuel efficiency and an increased adoption of electric vehicles. The pilot program, OReGO includes a flat per mile fee of 1.7 cents per mile (Oregon Department of Transportation [ODOT], 2019). The focus of the VMT tax was to explore alternatives to a per gallon fuel tax. However, the VMT tax concept could be expanded to include features that increase prices for congested areas, during rush hour or that also incorporate social costs associated with the transportation sector.

ZEV adoption. In 2019, Oregon legislature passed Senate Bill 1044 (SB 1044) which included legislation on ZEV adoption rates and incentives in Oregon. The legislation applied to battery electric vehicles, plug-in hybrid electric vehicles, and hydrogen fuel light duty vehicles (SB 1044, 2019). A light-duty vehicle includes passenger cars, sedans, station wagons, pickup trucks with a gross vehicle rating of 8,000 pounds or less, minivans equipped for passengers or cargo, sports utility vehicles, and crossover utility vehicles (SB 1044, 2019).

The legislation also detailed several goals including:

- Having 50,000 ZEVs registered in Oregon by 2020;
- Having 250,000 ZEVs registered in Oregon by 2025;
- By 2030, 25% of registered vehicles and 50% of new motor vehicles sold will be ZEVs; and
- By 2035, at least 90% of new motor vehicles sold will be ZEVS.

To achieve these goals, the legislation proposed incentives and procurement policies to increase ZEV adoption. These include providing rebates to customers that purchase electric vehicles established in House Bill 2017 (2017) and requiring state agencies to transition their current vehicle fleet to incorporate more ZEVs.

Co-Benefit Assessments – Reductions of PM 2.5

While the greenhouse gas emission reduction potential of these programs has been studied at great length, the co-benefits to air quality and health have not. The 2019 study by BEAR included air quality benefits by disaggregating national data to the state level and maintained several caveats (Roland-Holst et al., 2018). Other analyses have included applying a per mile emission factor to VMT to generate estimates. More detailed modeling of the impacts to air quality resulting from these policies provides local insight and understanding of a policy's potential impact and relationship among air quality, climate mitigation, and health. These analyses also can incorporate additional assumptions including things like changes in fleet turnover and improved emission control technology. A county- or state-level modeled approach can more easily be interpreted along with local considerations, such as emissions from other sources of concern. Notably, in Jackson County, Oregon, modeled emissions could be combined with data from other sources, such as wood smoke emissions, to perform a more complex health impact analysis or compare sources of emissions.

Climate and Emissions Modeling Approach

Two different models can be combined to assess the impact of Oregon's climate policy options on air quality. The first model is the Regional Strategic Planning Model (RSPM) used to model the impacts of policy on transportation. The second model is the Motor Vehicle Emissions Simulator (MOVES). This is a tool developed and maintained by EPA to model air emissions from the transportation sector.

Regional Strategic Planning Model (RSPM)

The RSPM is a model developed by the Oregon Department of Transportation (ODOT) specifically designed to estimate and forecast the effects of different policies on greenhouse gas emissions in the transportation sector. It allows for assessment and scenario planning so that local governments can evaluate future impacts of certain planning or policy actions. The model incorporates demographic information, development, transit services, transit lane types and miles, parking costs, ridesharing, and other criteria. This information is used to assess household-level vehicle characteristics and greenhouse gas emissions.

The RSPM model utilizes basic assumptions on how households manage the costs associated with transportation to model the impacts of pricing policy in the transportation sector. The model assumes that households maintain a relatively stable budget for transportation and shift costs within that budget to accommodate household needs (Gregor, 2015). The response to fuel prices is inelastic as long as a household can shift costs within their transportation budget. If the household can no longer shift costs, it will then reduce travel. This can be a gradual transition if the increased costs are phased in overtime (Gregor, 2015). The household concept allows for relationships between land use, transportation, and vehicles to be assessed (Gregor, 2015).

Outputs from the model include household travel, fuel and power consumption, and lifecycle greenhouse gas emissions (Gregor, 2015). The model allows for costs to influence VMT and travel and assess air pollutant emission with a basic emissions per mile calculation that does not include the more complex assessment available in the MOVES model.

Motor Vehicle Emissions Simulator (MOVES)

MOVES is a model developed and maintained by the EPA to model criteria pollutants, greenhouse gases, and air toxins emitted from mobile sources (EPA, 2019). States use MOVES to model emissions from cars, trucks, and non-highway vehicles under different conditions. The model uses information on vehicle types, time periods, geographical characteristics, operating information, and road types to calculate emissions associated with different operating processes like starting and running the vehicle (EPA, 2015). The EPA requires the model to be used in developing State Implementation Plans to meet Clean Air Act requirements (EPA, 2015).

The model has some limitations when it comes to modeling hybrid and plug-in hybrids, and it assumes that these vehicles meet the same emission standards as conventional internal combustion vehicles (EPA, 2019). However, it does allow a user to model fully electric vehicle fuel types. Because the model only includes emissions from vehicle operation, it does not account for emissions from the generation of electricity used in electric vehicles, assumes a fully electrified vehicle has no tailpipe or evaporative emissions, and also assumes that emissions from brake and tire wear are the same as conventional internal combustion engines (EPA, 2019).

The model currently utilized by DEQ to model criteria pollutant emissions is MOVES (2014a), including fine particulate matter emissions in the transportation sector. Although emissions estimates for greenhouse gases and air pollutants can be estimated from RSPM, MOVES allows for a more complete assessment of emissions because it incorporates more variables and takes into account things like starts, stops, brake wear, tires, and meteorology.

Assumptions in MOVES include energy consumption projections for future years based on light-duty vehicle greenhouse gas regulations and standards affecting light-duty vehicles starting with model year 2017 (EPA, 2019). This includes the standards for vehicle model year 2017 through 2025. After 2025 the standards are assumed to continue indefinitely (EPA, 2019).

Emissions from Electricity

MOVES does not model emissions from the production of electricity needed to power electric vehicles. However, these can be assessed based on activity data and Oregon-specific electricity mix emission factors. Oregon's electricity mix is primarily generated from hydroelectric dams. However, it currently does contain electricity from fossil-based resources, including natural gas and coal (Figure 2).

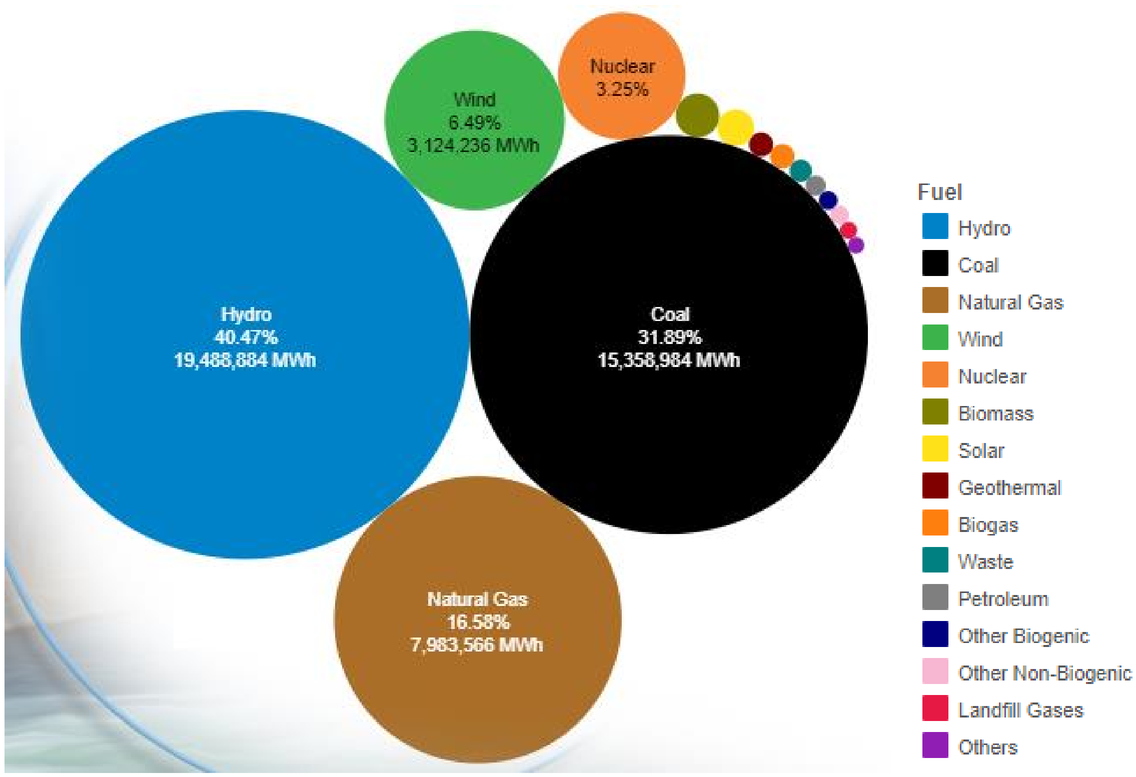


Figure 2. Fuels used to generate electricity consumed in Oregon. Data based on a three-year average (2014-2016) (ODOE, 2018).

In the 2016 legislative session, Oregon adopted Senate Bill 1547, which requires that coal-fired resources be removed from resources allocated to Oregon by 2030 (SB 1547, 2016). Along with a Renewable Portfolio Standard (RPS) and other measures, this requirement is expected to reduce the emissions intensity of Oregon's electricity over time. The investor-owned utility PacifiCorp serves power to Jackson County. Based on reported data and projections, the emissions intensity of PacifiCorp's load served in Oregon will drop from 0.713 MTCO2e/ MWh in 2010 to 0.127 MTCO2e/MWh by 2050 (DEQ, 2018) (Figure 3). This includes assumptions about the adoption of zero-emitting renewable electricity generating resources, and the phase out of coal power generation resulting from the requirements of SB 1547.

Figure 3. Projected emissions intensity of PacifiCorp's Oregon electricity mix. Data presented in MTCO2e per MWh 2021-2050 (DEQ, 2018).

Economic Benefit Analysis

There are multiple benefits associated with changes in emissions resulting from proposed carbon mitigation policies that can be monetized. The benefit in reduced emissions is captured in an assessment of avoided emissions. To estimate avoided emissions, a reference scenario is created and emissions estimates are developed. For comparison, the difference in emissions estimates from the reference scenario compared to a specific policy scenario is calculated. The difference, or avoided emissions, is used to assess the potential benefit of the policy attributed to those emission reductions.

There are established dollar values attributed to the reduction in metric tons of greenhouse gases, termed the Social Cost of Carbon (SCC) and the reduction in ton of PM 2.5, sometimes referred to as the benefit per ton. These dollar values when applied to the estimated avoided emissions allow a monetized cost or benefit to be associated with the avoided emissions that can be used in an economic analysis.

When assessing the monetized benefits over time discount rates are used to convert future dollars into net present values (NPV). Discount rates are needed because, in general, future costs and benefits are considered less valuable than current costs and benefits. A high discount rate places less significance on future impacts while a low discount rate places high significance on future impacts.

The SCC is published for several different discount rates however, the U.S. Interagency Working Group on Social Cost of Caron's price recommends using a 3% discount rate for analysis.

The Social Cost of Carbon (SCC)

The SCC is a value that quantifies climate damages in economic terms and represents the net economic cost of carbon dioxide emissions (Paul, Howard, & Schawrtz, 2017). It is expressed in dollars per ton and is the monetization of the damage done by one metric ton of carbon dioxide emitted into the atmosphere. The SCC includes quantified impacts from changes in energy demand, agricultural output and forestry, precipitation levels, CO2 fertilization, property lost to sea level rise, increased coastal storm damage, heat-related illnesses, some vectors of disease, water availability, and ecosystem impact (Paul et al., 2017).

It is important to calculate the SCC for the entire time that a policy is in place and impacting greenhouse gas emissions—not just a single year. Timing is important because greenhouse gases emitted in future years will cause increased damages due to the accumulation of emissions in the atmosphere.

Health Benefits of PM 2.5 Reductions

A health impact analysis can be used to quantify the negative health impacts of exposure to air pollutants and develop estimates of impact on populations. These estimates can be translated into economic impacts. Reductions in concentrations of air pollution lower the risk of negative health effects. Sector-based benefit per ton estimates from EPA are available to assess the economic impacts for avoided PM 2.5 emissions for on-road mobile sources. These estimates take into account PM 2.5 related premature deaths and illnesses and estimate the economic value through willingness-to-pay and cost-of-illness valuation techniques (Fann, Baker, & Fulcher, 2012).

Revenue from Pricing Greenhouse Gas Emissions

The carbon tax and all three of the cap and trade proposed policy scenarios modeled in this research price carbon emissions. This is typically done on a per metric ton basis and is one way of recouping the costs associated with the negative externalities of greenhouse gas emissions. In some instances, the price per ton of greenhouse gas is not equal to the full cost of the externalities. Revenue may be generated and emissions may be mitigated under these policy scenarios, but the entire cost of those emissions are not monetized in revenue generation and those costs are borne by society.

Research Questions, Hypotheses and Specific Aims

My research modeled and examined proposed climate policy in Oregon for changes in greenhouse gas and primary fine particulate matter (PM 2.5) emissions as a co-benefit of climate policy. As a case study, I focused on passenger car and light truck use in the Rogue Valley Metropolitan Planning Organization area in Jackson County, Oregon. I used modeled emission results from 2010, 2038, and 2050 to assess the climate and air quality health benefits through an assessment of avoided emissions. I modeled each scenario and monetized those benefits over time for an economic benefit analysis to the reference scenario.

My research focused on addressing:

- Which of the Oregon-proposed policies could achieve the largest reduction of transportation-related particulate matter and result in the greatest benefit to health due to improved air quality?
- How much do air quality benefits of reduced fine particulate matter contribute to the economic impacts of the proposed policies?

I hypothesized that transportation-specific policy, such as Oregon's increased ZEV adoption program, would have a greater impact on particulate matter emission than economy-wide carbon pricing policies. Among the carbon pricing options, the policy that places the highest price on carbon would produce the greatest reduction in greenhouse gases and fine particulate matter. Policies that have a higher price in the initial years will produce more economic benefit related to emission reductions and health.

Specific Aims

This research included the following specific aims:

1. Construct reference scenario transportation model parameters utilizing RSPM to create outputs for the Motor Vehicles Emissions Simulator (MOVES).
2. Determine and modify the changes in RSPM parameters of the reference scenario to reflect the individual policy scenarios.
3. Model emissions resulting from each scenario through MOVES and compare greenhouse gas and particulate matter emissions under the proposed scenarios.
4. Monetize the health benefit of MOVES particulate matter outputs for each scenario.
5. Utilize the monetized health benefit information as an input into an economic analysis comparing the benefits of each scenario.

Chapter II

Methods

To assess fine particulate matter emission, PM 2.5, and changes as a result of potential climate mitigation policy in the transportation sector for Jackson County I developed one reference scenario and six policy scenarios based on public information and reports describing each of the Oregon policy options. I modeled each of these transportation scenarios with an open source model, RSPM. Each scenario was modeled for a baseline year 2010, 2038, the year the Regional Transportation Plan would be fully implemented and a future year, 2050. RSPM outputs from each policy scenario were configured and used as inputs into EPA's MOVES model. The MOVES model created daily estimates of greenhouse gases and particulate matter from tire wear, brake wear and exhaust and activity data including VMT per vehicle type. VMT estimates were used to calculate emissions from the electricity sector from electric vehicle use. In combination, these emission estimates were utilized to calculate annual emissions and compared to the reference case. The change in greenhouse gas and PM 2.5 emissions from the reference scenario were monetized to calculate the benefit of avoided emissions.

Scenario Development

This research evaluated six different policy scenarios and a reference (REF) scenario that incorporated all of the base assumptions of the RVMPO's original model. The reference scenario established a baseline case to compare each proposed policy scenario and to calculate avoided emissions. All carbon-pricing scenarios were assumed to start in calendar year 2021 as recently proposed in Oregon's House Bill 2020 (HB 2020) and the VMT Tax policy was assumed to be implemented earlier, in 2010. The following is a description of the scenarios tested in this study including a summary in Table 2.

Table 2. Summary of policy scenarios.

<table>
<tr><th>Scenario Name</th><th>Scenario Policy Basis</th><th>Description</th></tr>
<tr><td>Reference (REF)</td><td>Statewide Transportation Strategy</td><td>Oregon's proposed strategy for reducing emissions in the transportation system.</td></tr>
<tr><td>VMT Tax</td><td>Senate Bill 810 (2013)</td><td>Oregon vehicle owners pay a per-mile road usage charge in place of the existing fuel tax on gasoline and diesel.</td></tr>
<tr><td>Carbon Tax</td><td>Report from Senate Bill 306 (2013)</td><td>Places a carbon tax on greenhouse gas emissions statewide as a new revenue option in $ per ton.</td></tr>
<tr><td>Cap and Trade (Low-CT)</td><td>House Bill 2020 (2019)</td><td rowspan="3">Requires an economy wide cap on greenhouse gas emissions. Creates a market-based mechanism for covered entities to purchase allowances or implement emission reductions to comply.</td></tr>
<tr><td>Cap and Trade (Medium-CT)</td><td>House Bill 2020 (2019)</td></tr>
<tr><td>Cap and Trade (High-CT)</td><td>House Bill 2020 (2019)</td></tr>
<tr><td>ZEV Adoption</td><td>Senate Bill 1044 (2019)</td><td>Adopts transportation electrification goals for passenger and light duty vehicles.</td></tr>
</table>

Reference scenario (REF). This scenario established a baseline for comparison and was constructed to model emissions from RVMPO's existing transportation sector and project emissions based on current existing policy. The assumptions used in this scenario were RVMPO's original strategic assessment assumptions for the transportation sector (Moore, 2016). The study used various data sources including census data, travel demand model outputs, state-level programs and policy assumptions, federal standards and adopted regional strategies (Moore, 2016).

Carbon tax. Carbon taxes are based on a per metric ton cost. This research modeled the carbon price proposed in Northwest Economic Research Center's (NERC) 2013 study on a proposed carbon tax in Oregon which included a base year price of $10 increasing annually by $10 and capping off at $60 (Liu & Renfro, 2013). For economic analysis purposes, the initial year for the carbon tax was assumed 2021.

Cap and trade. Three cap and trade scenarios were tested based on the assumption that the full price of allowances, where one allowance equals one metric ton of carbon dioxide equivalent, in the transportation sector would be passed on to consumers. The prices modeled were in dollars per metric ton of carbon dioxide equivalent. A gallon of gasoline or diesel emits approximately 0.009 metric tons of CO2e. Since it is assumed that the full price per emissions is passed down to consumers per gallon purchased, approximately 0.09% of the allowance price is passed on to consumers. For example, if an allowance is $16 the cost passed down to consumers is approximately $0.14 cents per gallon.
This research examined three cap and trade pricing scenarios- a low pricing scenario (Low-CT), a medium pricing scenario (Medium-CT) and high pricing scenario (High-CT). The scenarios assumed the pricing costs associated with Oregon's most recent cap and trade proposal, HB 2020, as modeled in the Berkeley Economic Advising Research (BEAR) listed in Table 1. This study, commissioned by Oregon's Climate Policy Office,

looked at policy options under cap and trade that were actively being considered during the 2019 legislative session (Roland-Holst et al., 2018).

VMT tax. I tested one VMT Tax scenario based on the OReGO program of 1.7 cents per mile, for all model years. This scenario assumes the VMT tax would be in place of the state's existing gas tax. As a result, this scenario did not include any state gasoline tax. Although this policy was proposed in 2013 for purposes of modeling I assumed this policy was initiated in 2010. This was the only active policy in the 2010 model year.

Increased zero-emission vehicle adoption (ZEV Adoption). To model Oregon's ZEV adoption policy under SB 1044, I assumed that the goals proposed in the policy for new motor vehicles sold annually applied to light duty passenger vehicles including autos and light-duty trucks and that by 2050, 100% of new passenger vehicle sales would be either a plug-in hybrid (PHEV) or fully electric vehicle (EV).

To adopt these purchasing goals in the RSPM model I modified the "phev characteristics" file starting in 2020. This parameter determines the ratio of plug-in PHEV and EV to traditional internal combustion engines (ICE) and hybrid electric vehicles (HEV). Since SB 1044 was enacted in 2019 I assumed that the first year the policy could have an impact is on vehicles sold in 2020. Since both PHEVs and EVs are considered ZEV under SB 1044 I did not change the assumption on the ratio of EVs to PHEVs from the reference scenario or modify any range or miles per kilowatt-hour assumptions in RSPM. However, this scenario incorporated other assumptions:

- To model the first sales goal, that at least 50% of new vehicles sold would be ZEV by 2030, I increased the ratio of each model year from 2020 to 2030 at a constant rate that would be modeled as a ZEV from the reference percentage in 2019 to 50% in 2035.
- I next adjusted the percentage of new vehicles that were ZEVs at a constant rate from model year 2030 to model year 2035 when 90% of vehicles sold must be EVs or PHEV vehicles.
- Finally, I increased the adoption of ZEVs from 2035 to 2050 at a constant rate so that in 2050 100% of the new autos and light duty trucks were either EV or PHEVs.

The results of incorporating the purchasing goals described in SB 1044 into the fleet composition for the ZEV Adoption scenario in 2038 and 2050 are presented in Figure 4 and Figure 5.

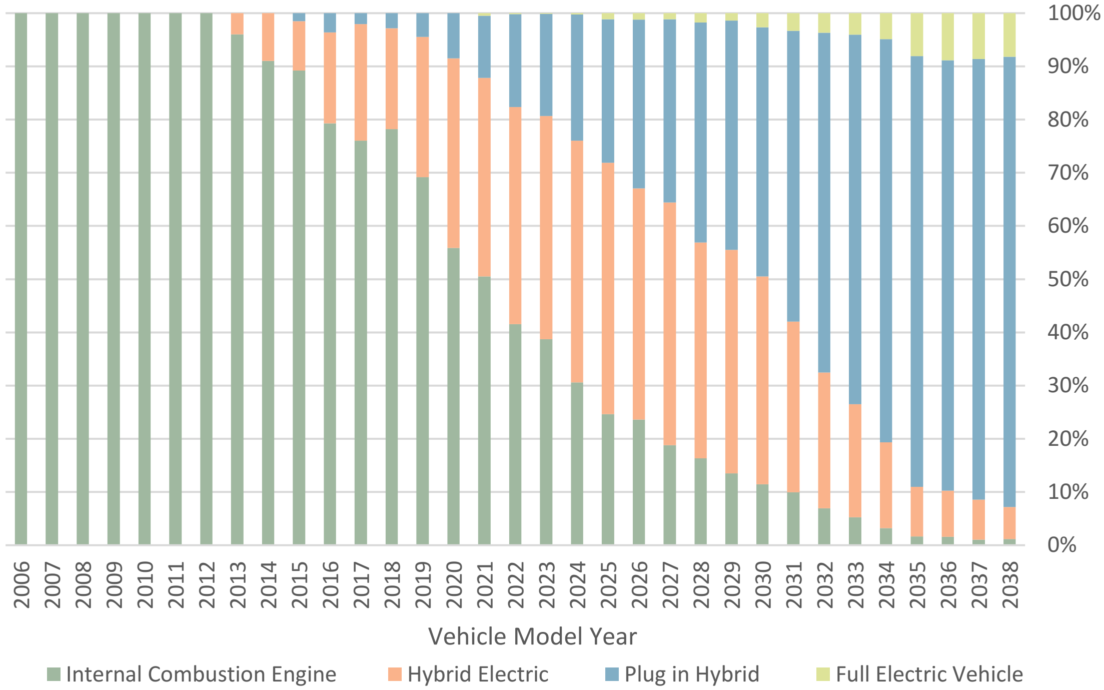


Figure 4. 2038 fleet composition by engine type and vehicle model year.

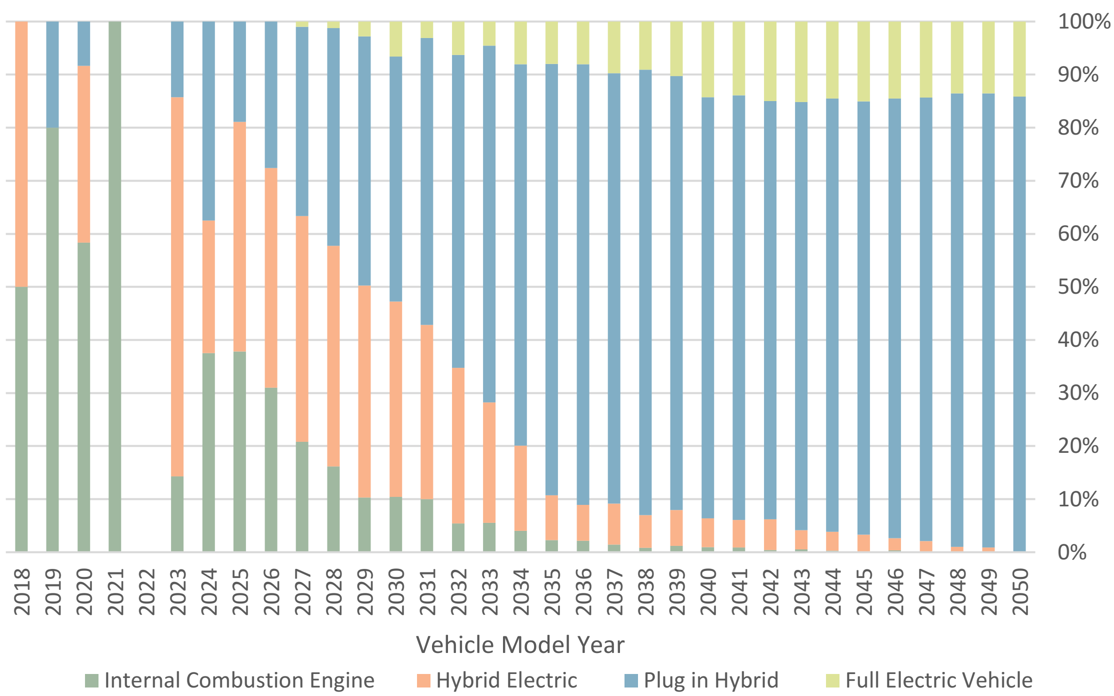


Figure 5. 2050 fleet composition by engine type and vehicle model year. The RSPM model results for the ZEV Adoption 2050 did not include any vehicle types that were model year 2022 so no data appears for that vehicle model year.

Modeling the Transportation Sector in RSPM

The specific version of RSPM used in this research to model the impact of Oregon's proposed climate policies in the transportation sector was RSPM 3.7 populated with the base parameters provided by the RVMPO. The RVMPO includes the urbanized areas of Jackson County, Oregon (Figure 6). The RSPM model used in this study incorporated all of the inputs utilized for the RVMPO 2016 strategic assessment work done in partnership with ODOT and the Oregon Department of Land Conservation (DLCD) (Moore, 2016). For the purposes of my research, I assumed the full implementation of adopted land use and transportation plans and modeled the same years as the RVMPO model 2010, 2038, and 2050. A complete list of the adopted parameters used in this study are available in Appendix B of the RVMPO February 2016 Strategic Assessment of Transportation and Land Use report (Moore, 2016).

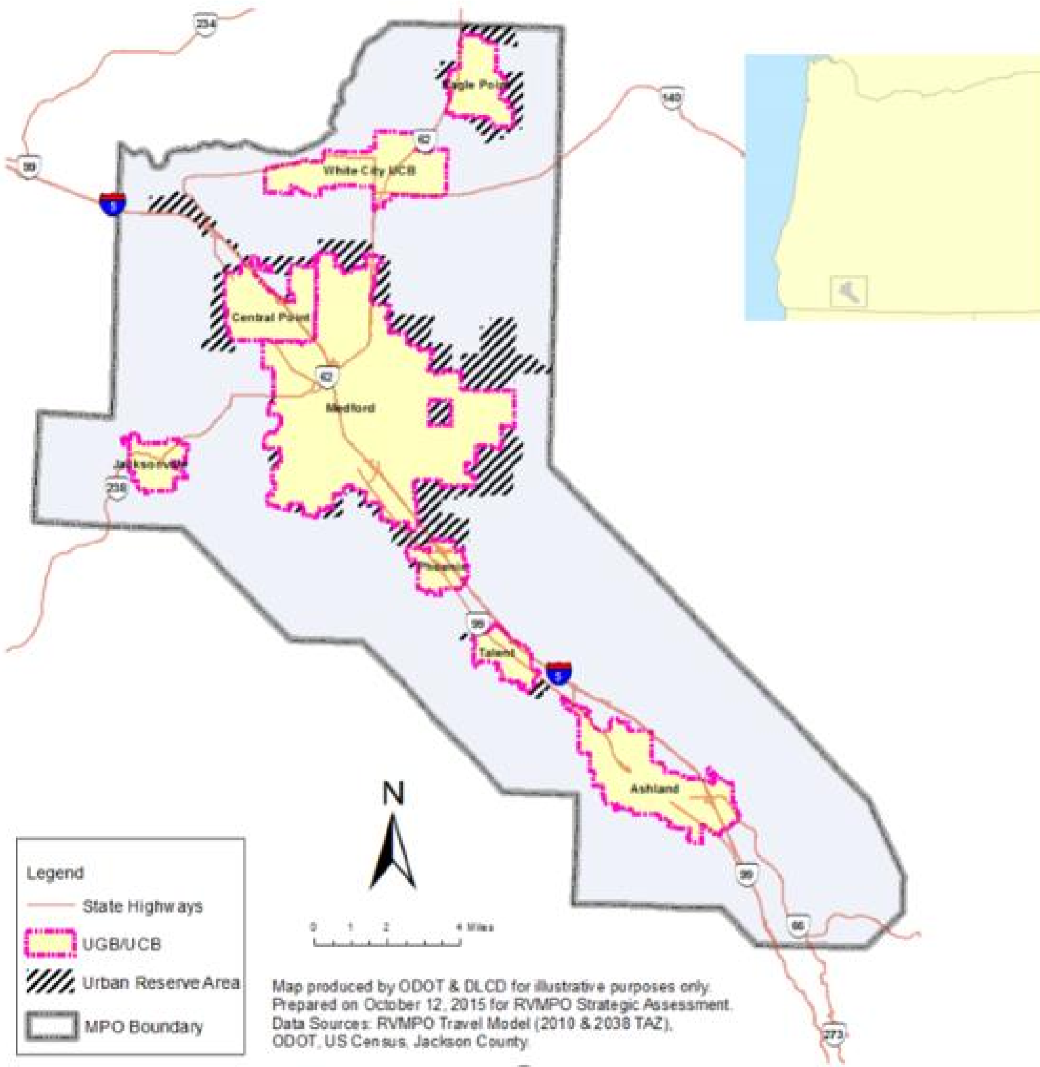


Figure 6. RVMPO Strategic Assessment Study Area (Moore, 2016).

For each scenario and model year I modified costs, taxes or vehicle technology adoption rates in the proper input files in the RSPM model as appropriate. RSPM creates many different outputs for analysis for each year. For this research I used vehicle population including type and age, fuel type, vehicle miles traveled (VMT) and road type outputs for each model year as inputs into EPA's MOVES model to model air quality emissions.

Modeling Emissions in MOVES

The second modeling step for my research required modeling emissions under each of the scenarios based on the established parameters and RSPM inputs. For the purposes of this research, the specific model used was MOVES (2014a). MOVES parameters and inputs were tailored for each scenario and model year based on RSPM outputs. The emissions outputs data from all of the scenarios included tailpipe greenhouse gas emissions in metric tons of carbon dioxide equivalent (MTCO2e) per day and particulate matter (PM2.5) emissions from tailpipe, brake and tire wear in tons per day.

To capture temporal impacts such as meteorological changes, the impact of time of day and days of the week I modeled emissions for a 24-hour period on a weekday and weekend in each season; January, April, July and October. To calculate annual emissions, I multiplied the pollutant output by the number of days in each quarter and totaled emissions for the year.

Default data from MOVES was used for meteorological data, average speeds, fuel supply, fuel formulation, fuel use fraction, and to apportion RSPM daily VMT to hourly data. RSPM data outputs were used in MOVES for vehicle age distribution, fuel mix, road type, vehicle type counts, and daily VMT. With the exception of road type, outputs RSPM outputs were only reformatted or translated into proportions as inputs to MOVES.

RSPM attributes VMT to three road types: “freeway,” “arterials,” and “other.” MOVES has two road types “urban restricted” and “urban unrestricted.” For purposes of this research, the three RSPM road types were mapped to the most similar MOVES road type. The RSPM “freeway” was mapped to the “urban restricted” road types in MOVES and “arterials” and “other” were considered urban restricted. A summary of MOVES data inputs and data sources is listed in Table 3.

Table 3. Data sources for MOVES models runs.

MOVES Data Files	**Data Source**	**Description**
Age distribution	RSPM	The percent of vehicles in each age class by vehicle type produced by RSPM was the basis for the age of the fleet input into MOVES for each model run.
Average speeds	MOVES Default	Average speed default data provided by MOVES was used for speed estimates. This includes speed distributed by road type, vehicle type, and time of day.
Fuel supply	MOVES Default	The default market share and composition of fuel blends was used for modeling.
Fuel formulation	MOVES Default	MOVES default fuel formulations were used for modeling liquid fuels including gasoline, diesel, ethanol and biodiesel.
Fuel usage fraction	MOVES Default	MOVES defaults were used to assign the percentage of E-85 users in Oregon.
Alternate vehicle and fuel technology	RSPM	RSPM outputs were used to adjust the percentage of vehicles using each fuel type. This file was adjusted to model fully electric vehicles.
Meteorological data	MOVES Default	Default MOVES data was used and includes temperature and humidity inputs by month and hour.
Road type	RSPM	RSPM VMT by road type were mapped to MOVES road types and input by vehicle type.
Source type population	RSPM	The number of automobiles and light-duty trucks was an output from RSPM that was directly input into MOVES.
Vehicle type VMT	RSPM	Daily VMT outputs by vehicle type from RSPM were used for all months and days (weekends and weekdays).
Hour VMT fraction	MOVES Default	MOVES provides national defaults for hour activity VMT fractions.
Inspection and maintenance	Not in use	No inspection and maintenance scenarios were modeled.
Starts	MOVES Default	MOVES default vehicle start values were used for all model runs.

Emissions from Electric Vehicles

MOVES does not calculate emissions associated with the electricity used to power electric vehicles. To account for these emissions, I calculated emissions estimates based on activity data. I used the VMT output values for electric vehicle modeled in MOVES and efficiency (miles per MWh) assumptions for passenger cars and light duty trucks in RSPM to calculate the total megawatt hours attributed to electric vehicles for each year and each scenario.

To calculate greenhouse gas emissions, I multiplied the annual megawatt hours calculated above by the greenhouse gas emission factor for PacifiCorp in the specific model year (Table 4).

Table 4. Greenhouse gas emissions factors for PacifiCorp.

Emission Year	**2010**	**2038**	**2050**
(MTCO2e / MWh)	0.713	0.100	0.127

Data presented in metric tons of carbon dioxide equivalent per megawatt hour (MTCO2e/MWh) (DEQ, 2018).

The majority of particulate matter emissions in the electricity sector originate from the combustion of coal. The resource mix for PacifiCorp is not projected to include coal after 2030 (SB1547, 2016). The only fossil generating resource is projected to be natural gas, which is not a large source of fine particulate matter. For purposes of this research, I calculated the PM 2.5 emissions as follows:

- Total kilowatt-hour (KWh): I calculated the total annual power needed for electric vehicles based on the annual VMT values for electric vehicles in each scenario produced from MOVES and the efficiency assumptions in the RSPM model (miles per KWh) by vehicle type.

- KWh attributed to fossil generation: I assumed that natural gas would be the only electricity source in PacifiCorp's resource mix with PM 2.5 emissions and that the portion of KWh for each of the scenarios that would be generated by a natural gas power plant would equal the share of market purchases in the model year.
- Total amount of natural gas: I calculated the total amount of natural gas, in British thermal units (Btu), that would be needed to generate the estimated KWh based on the 2018 EIA value for the average annual heat rate of a natural gas facility (Btu per KWh) and converted to MMBtu.
- PM 2.5 emissions: I then applied the EPA PM 2.5 total emission factor in (lb/MMBtu) to the calculated amount of natural gas for each scenario and converted pounds to tons for final assessment.

Economic Assessment

The monetization of the health impacts of changes in greenhouse gases and PM 2.5 under each scenario were used as an input into a basic spreadsheet economic model to assess several of the benefits of each policy scenario. This analysis took into account revenue generated from carbon pricing, the social cost of avoided carbon emissions and the health benefits of improved air quality based on avoided PM 2.5 emissions.

The assessment extended from calendar year 2010 through 2050. Since modeled data existed only for 2010, 2038 and 2050, data in-between years was linearly interpolated. I adjusted cost inputs for inflation; all dollar amounts are calculated and presented in 2019 dollars. Calculations were done using a discount rate of 3% and 5% and the results are provided in net present values (NPV). The individual value of each benefit was assessed as well as total NPV.

In the economic cost benefit for each scenario I included the following:

- Carbon pricing revenue generated
- Health benefit of avoided fine particulate matter emissions
- SCC benefit of avoided greenhouse gas emissions

The carbon pricing policies were assumed to start in 2021. Carbon pricing revenue was developed by multiplying the policy price per ton dollar value starting in 2021 by the total emissions estimated for a particular year. Emission estimates for years in between modeled years were linearly interpolated.

Avoided PM 2.5 emissions were monetized and assessed using EPA's sector-based PM 2.5 benefit per ton estimates, which are based on national averages (Table 5). The benefit of reduced PM 2.5 emissions was determined by calculating the difference in emissions of the policy scenario from the reference scenario and multiplying it by the benefit per ton dollar value adjust to 2019 dollars. Benefit values from 2010 through 2030 were calculated using EPA's inflation adjusted 2016 benefit per ton value for on-road mobile sources. Starting in model year 2030, the inflation adjusted 2030 benefit per ton value for on-road mobile sources was used.

Table 5. Sector-based health benefit per ton estimates for on-road mobile sources.

	2016	2030
On-road mobile sources	$ 430,816	$ 538,520

Data presented in 2019 dollars (EPA, 2018c).

Similar to calculating the benefits of reduced PM 2.5, to estimate the benefit of avoided greenhouse gas emissions I calculated the difference in greenhouse gas emissions emitted in each scenario from the reference scenario. I then multiplied the metric tons in avoided emissions by the SCC. The SCC values utilized in this analysis are from the Interagency Working Group on the Social Cost of Greenhouse Gases 2016 technical supporting document. The values were adjusted for inflation and are listed in Table 6.

Since the SCC value is only provided for every 5 years I linearly interpolated SCC values for in-between years. I performed this assessment with both the 3% discounted and 5% discounted SCC values.

Table 6. Social Cost of Carbon (SCC) 2010-2050.

Emissions Year	Average estimate at 5% discount rate	Average estimate at 3% discount rate
2010	$ 12.44	$ 38.55
2015	$ 13.95	$ 44.77
2020	$ 15.22	$ 51.83
2025	$ 17.76	$ 57.01
2030	$ 20.30	$ 62.19
2035	$ 22.83	$ 68.41
2040	$ 26.64	$ 74.63
2045	$ 29.17	$ 79.81
2050	$ 32.98	$ 86.03

Presented in 2019 dollars per metric ton (Paul et al., 2017).

Chapter III

Results

The modeled data analyzed in this research demonstrated changes and reductions in future years for both greenhouse gases and PM 2.5 emissions for all policies when compared to the reference scenario. However, the timing of the implementation of the policy and the level of impact varied depending on the policy approach and, for pricing policies, the magnitude of the costs.

Greenhouse Gas Emissions

In 2010 modeled emissions data for the REF scenario were 630,281 metric tons of carbon dioxide equivalent (MTCO2e) (Figure 7). Since the VMT Tax scenario was the only active policy during this initial year all other model results for 2010 were equal to the REF scenario. Greenhouse gas emissions for the VMT Tax scenario in 2010 were 631,796 MTCO2e, slightly greater than the REF scenario (Figure 7). This increase from the REF scenario indicates that the VMT Tax, at that time, did not send an equivalent or more stringent price signal to households as the fuel tax cost assumption inherent in the REF and all other scenarios in 2010.

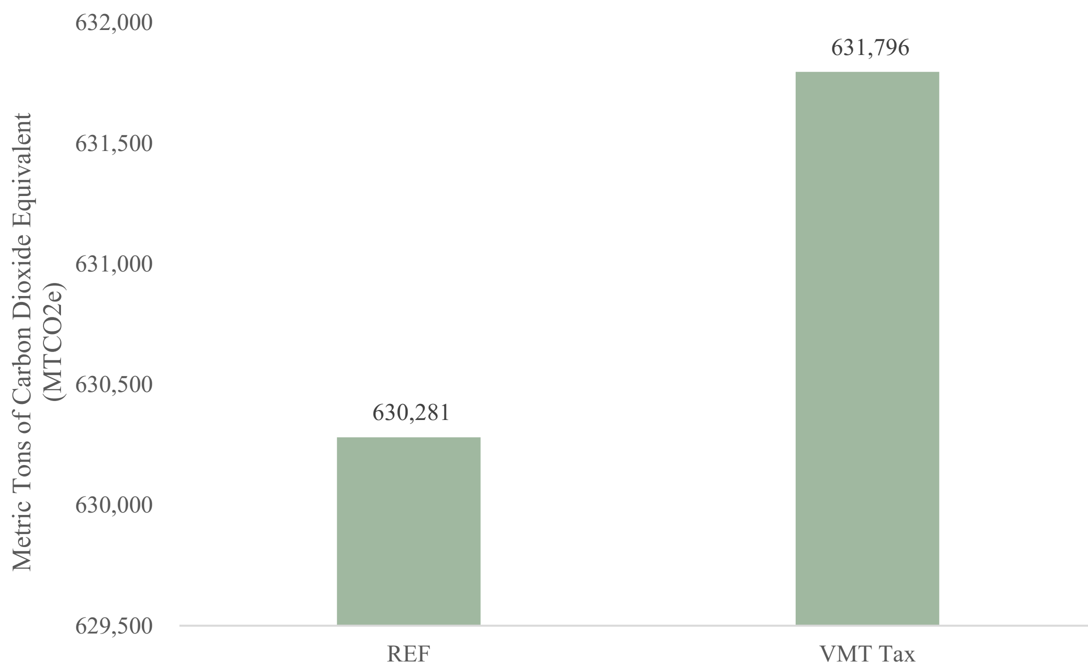


Figure 7. 2010 annual greenhouse gas emissions for REF scenario and VMT Tax.

In 2038, the REF scenario greenhouse gas emissions declined from the 2010 value of 630,281 to 180,848 MTCO2e (Figure 8). In 2050, the model results for the REF scenario reduced further to 140,012 MTCO2e (Figure 9). Emissions reductions in the REF scenario were driven by the baseline assumptions in the Rogue Valley RSPM model, including community design inputs and the adoption of the Statewide Transportation Strategy (Moore, 2016). The other scenarios produced greenhouse gas emission results that were lower than the REF scenario for 2038 and 2050. Emissions ranged from a total of 171,000 to 179,391 MTCO2e in 2038 and 124,564 to 138,434 MTCO2e in 2050 (Figures 8 & 9).

In 2038 greenhouse gas avoided emissions for the six-scenarios ranged as high as 9,677 MTCO2e for the High-CT (Figure 8). The model results for that year indicated that the scenario with the second greatest avoided greenhouse gas emissions was the ZEV

Adoption scenario at 7,563 MTCO2e. The Medium-CT scenario at 5,155 MTCO2e followed this.

The Low-CT scenario and Carbon Tax scenario produced results that were similar to one another. The similarity is a result of the 2038 carbon tax price and Low-CT allowance price being very close, within $4 dollars of each other. After that time, the carbon tax remains constant at $60 dollars while the Low-CT scenario continues to increase. The impact of the increase compared to the carbon tax scenario is apparent in the 2050 results (Figure 9). In that year, the Low-CT scenario resulted in greater avoided emissions than the Carbon Tax. The VMT Tax policy demonstrated the least change in 2038, with avoided emissions equal to 1,458 MTCO2e. (Figure 8).

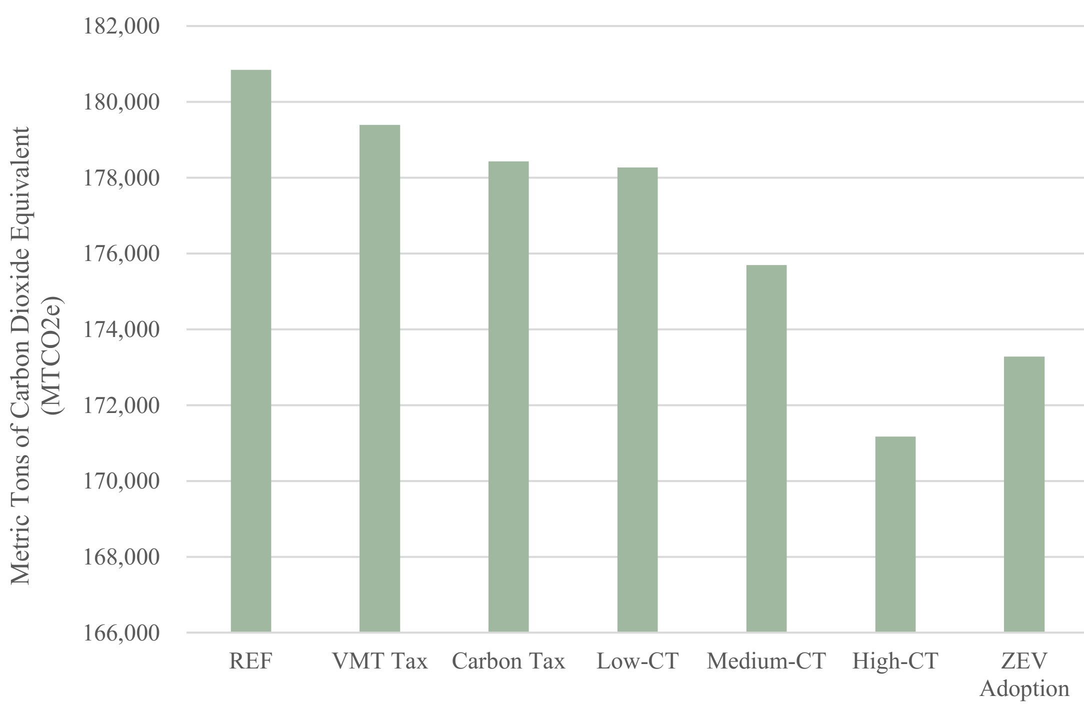


Figure 8. 2038 total annual greenhouse gas emissions by scenario.

For the 2050 model year, again all of the scenarios produced reductions when compared to the REF scenario. In contrast to 2038 results, the greatest reduction in greenhouse gas emissions occurred in the ZEV Adoption policy scenario followed by the High-CT pricing scenario. Those scenarios resulted in a 9-11% reduction in greenhouse gas emissions from the REF scenario (Figure 9).

The VMT Tax and Carbon Tax model results demonstrated the smallest reduction, approximately 1% of total emissions in 2050. The Carbon Tax resulted in the least amount of avoided emissions, meaning that in 2050 the $60 per ton price on carbon was less impactful than the VMT Tax per mile fee.

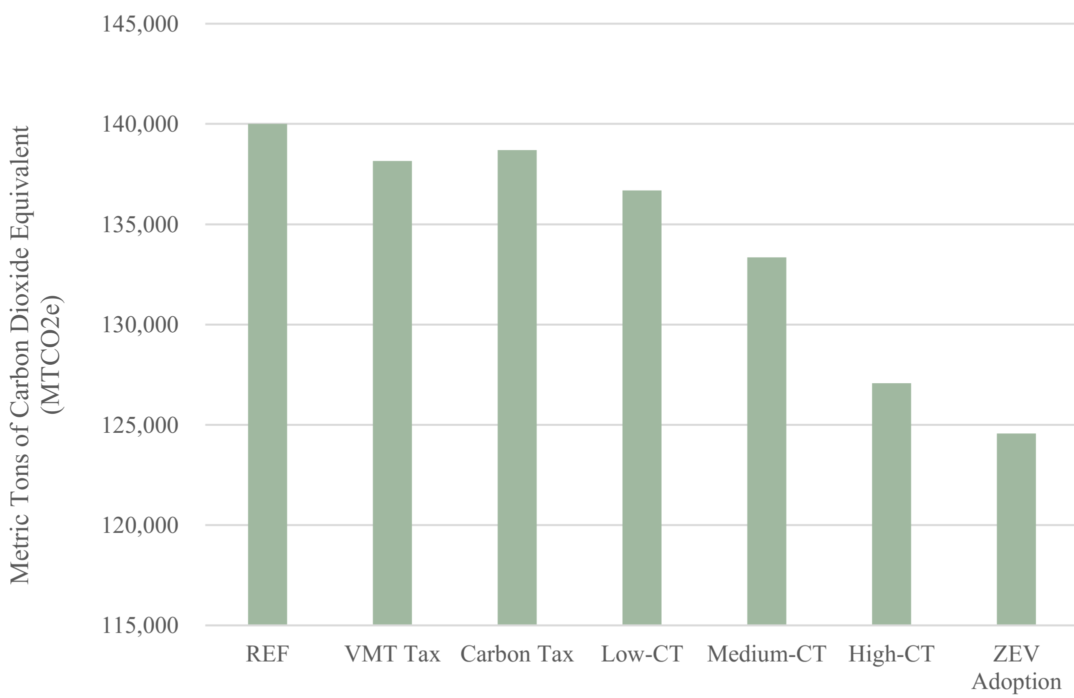


Figure 9. 2050 total annual greenhouse gas emissions by scenario.

Emissions from Electricity Generation

Emissions from the generation of electricity needed to power electric vehicles is another contributor to emissions in the transportation sector. The ZEV Adoption policy scenario had the most electric vehicles and thus resulted in the greatest amount of greenhouse gases (Figure 10) and PM 2.5 emissions (Figure 11) from electricity generation.

When compared to overall greenhouse gas emissions, emissions produced from electricity generation made up less than 1% of total emissions for the REF and in the majority of the policy scenario model results for 2038 and 2050. The one exception is the ZEV Adoption 2050 scenario where greenhouse gas emissions from electricity generation accounted for a little over 2% of emissions. PM 2.5 emissions from electricity generation to power electric vehicles followed a similar pattern (Figure 10).

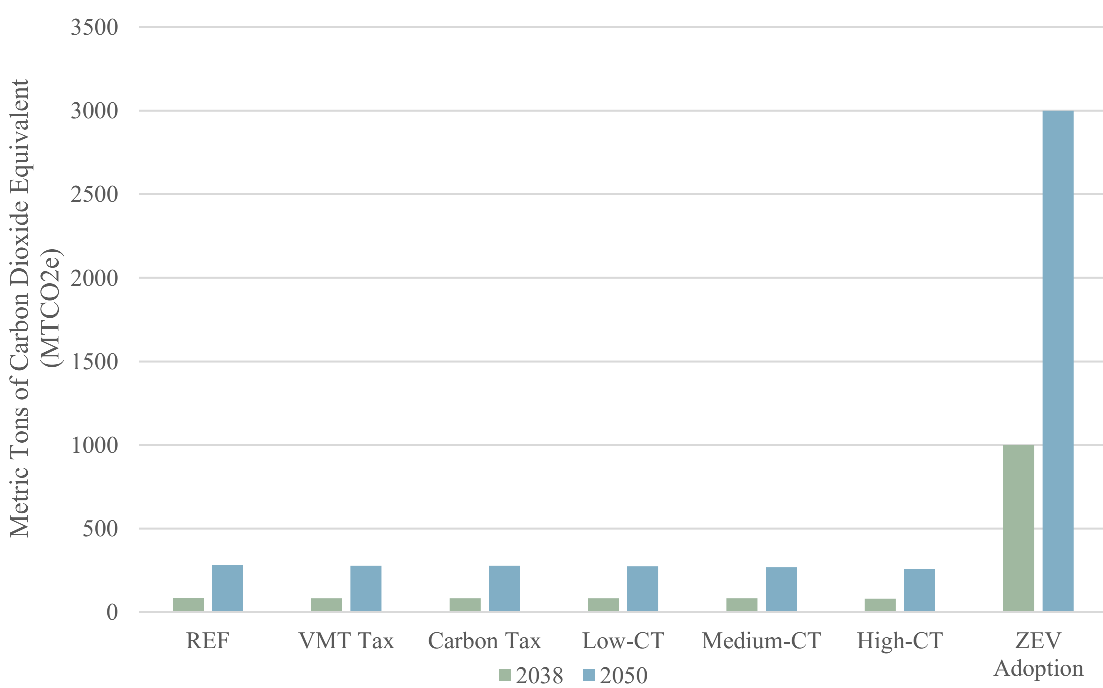


Figure 10. Greenhouse gas emissions from electricity generation needed to power electric vehicles by scenario and year.

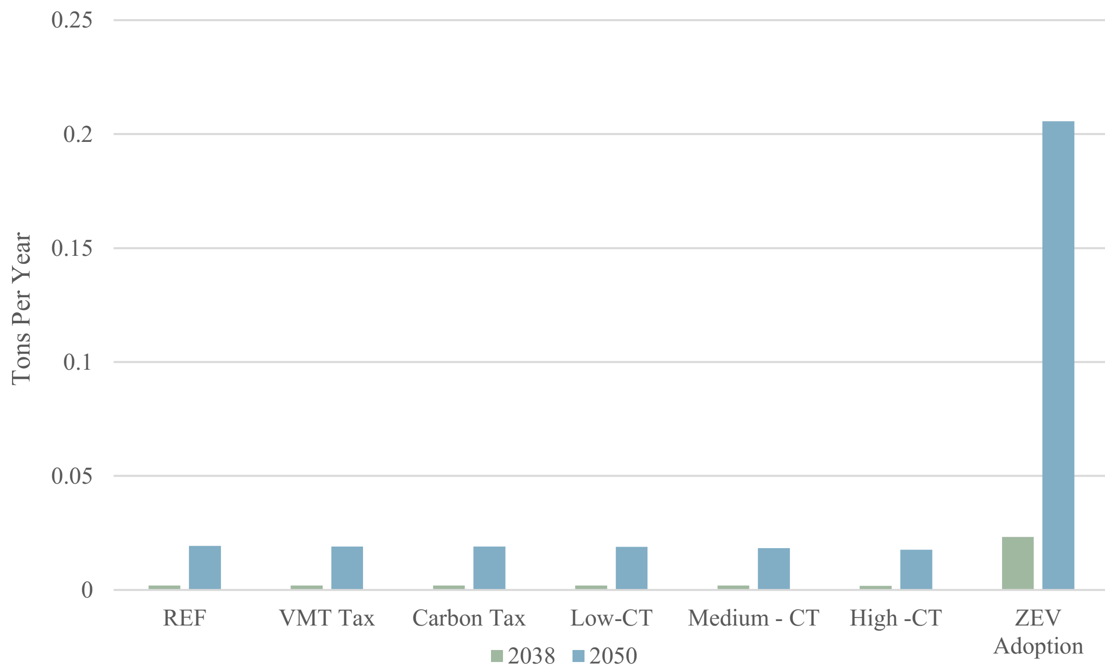


Figure 11. PM 2.5 emissions from electricity generation needed to power electric vehicles by scenario and year.

In terms of greenhouse gas emissions intensity for the entire modeled fleet (greenhouse gas emissions per VMT), in total the ZEV Adoption scenario had the least emissions-intensive results in both 2038 and 2050 (Figure 12). The emissions intensity of all other scenarios had no notable difference from the REF scenario. The 2050 ZEV Adoption policy had the most efficient and least emissions-intensive fleet of all modeled scenarios.

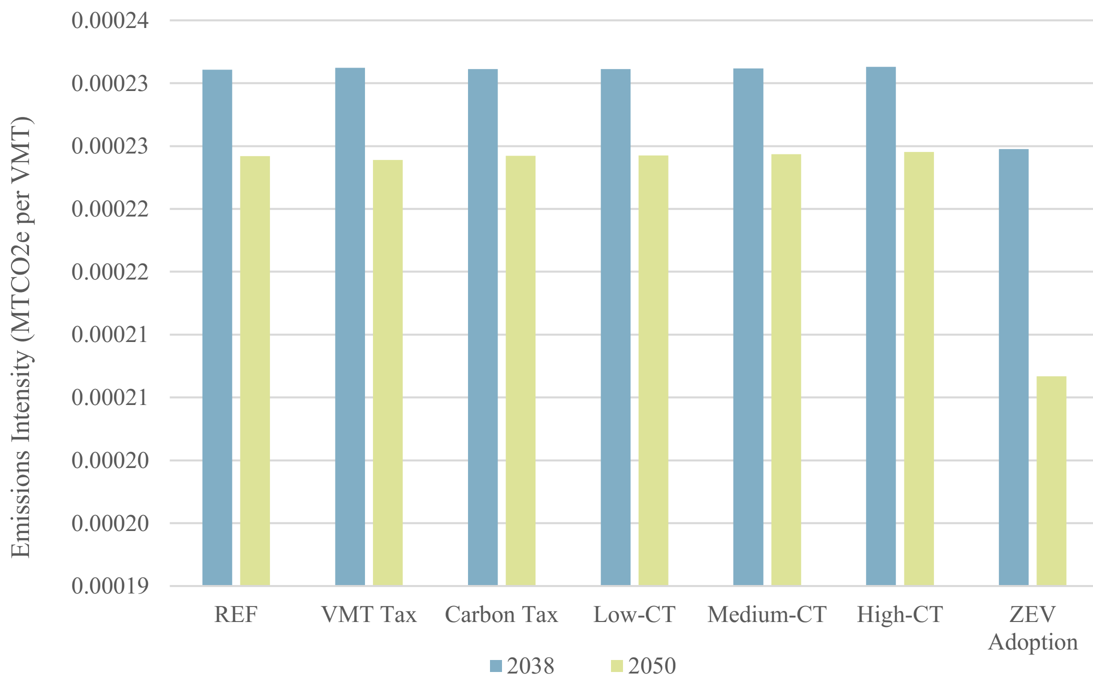


Figure 12. Fleet wide emissions intensity in MTCO2e per VMT for all scenarios in 2038 and 2050.

In summary, the High-CT scenario resulted in the greatest greenhouse gas avoided emissions in 2038 while the ZEV Adoption policy resulted in the greatest avoided emissions in 2050 (Figure 13). The Medium-CT scenario followed for both years. In 2038, the Carbon Tax and Low-CT results were similar while the VMT Tax scenario produced the least reductions. However, the Carbon Tax policy resulted in the least amount of avoided emissions compared to the REF scenario in 2050 (Figure 13).

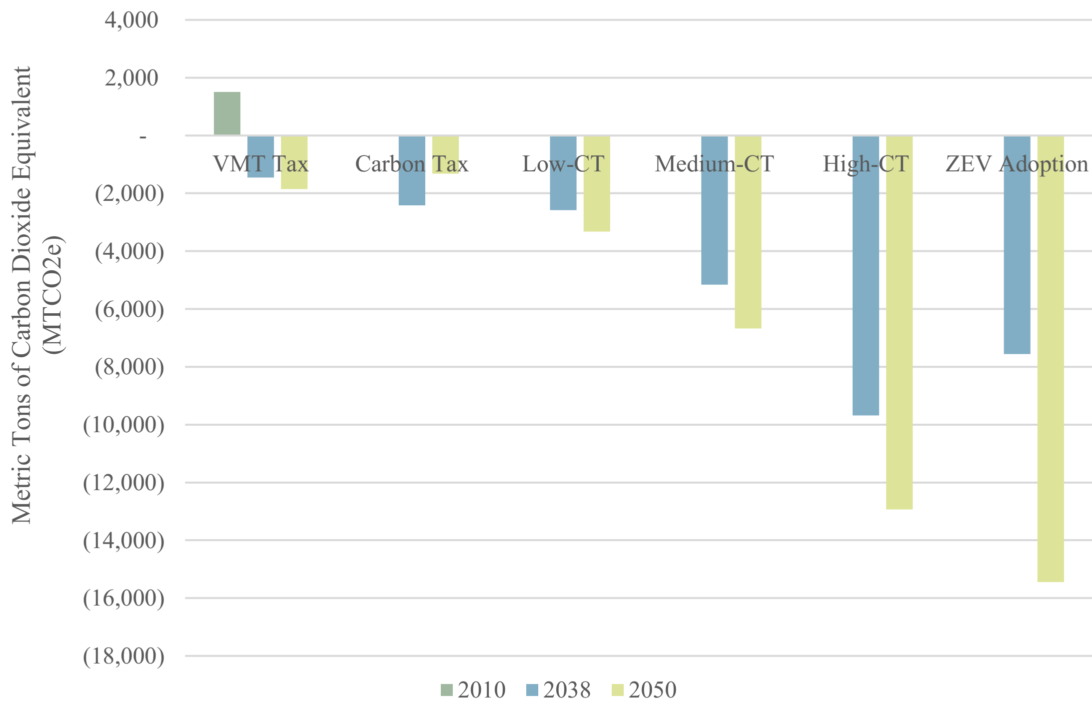


Figure 13. Avoided greenhouse gas emissions for all years.

PM 2.5 Emissions Results

Similar to the greenhouse gas results in 2010, the emissions of PM 2.5 for the VMT Tax scenario were higher than that of the REF and all other policy scenarios (Figure 14). Since the VMT Tax scenario was the only active policy during this initial year all other model results for 2010 were equal to the REF scenario.

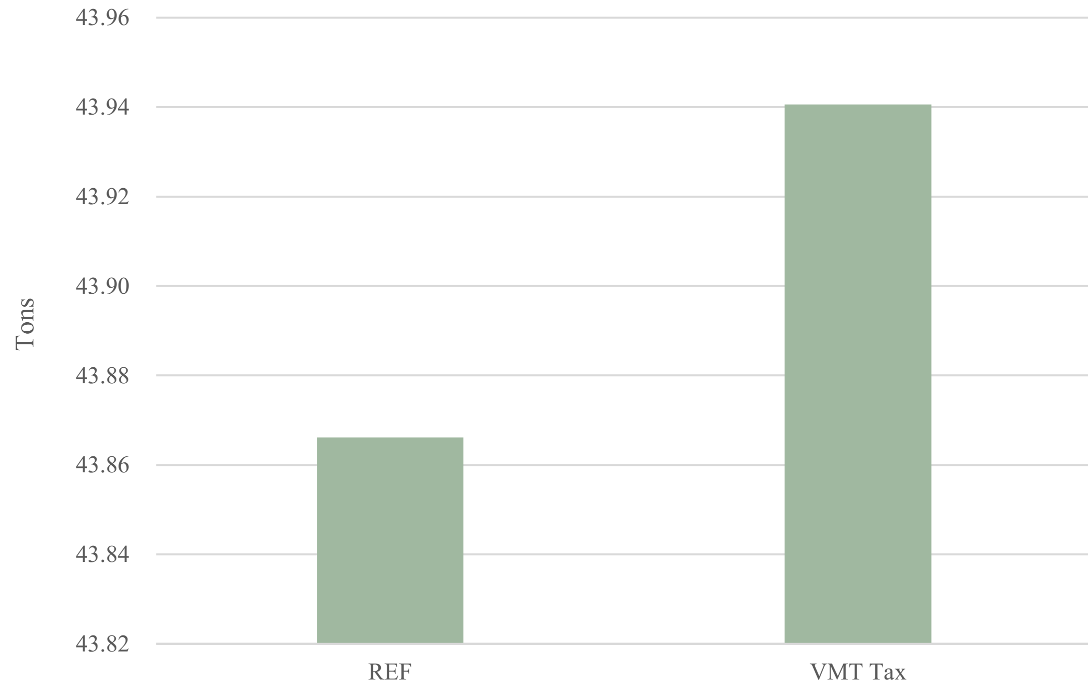


Figure 14. 2010 annual PM 2.5 emissions for the REF and VMT Tax scenarios.

All policies demonstrated decreases in PM 2.5 emissions when compared to the REF scenario for 2038 (Figure 15). In 2050, all policies demonstrated reductions in direct emissions from vehicles (exhaust, brake and tire wear). However, in 2050, when the emissions from the generation of electricity used to power vehicles is included the ZEV Adoption policy actually demonstrated a small increase in PM2.5 emissions (Figure 16). This resulted from the assumption that the market power produced in 2050 would be produced from natural gas.

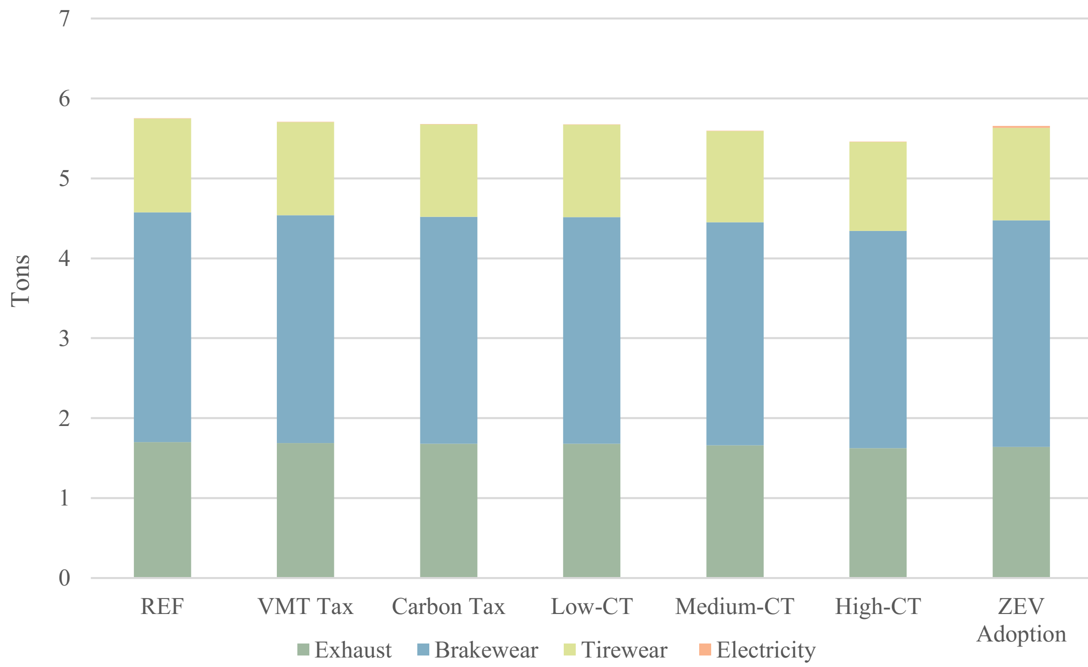


Figure 15. 2038 annual tons of PM 2.5 emissions by scenario and source.

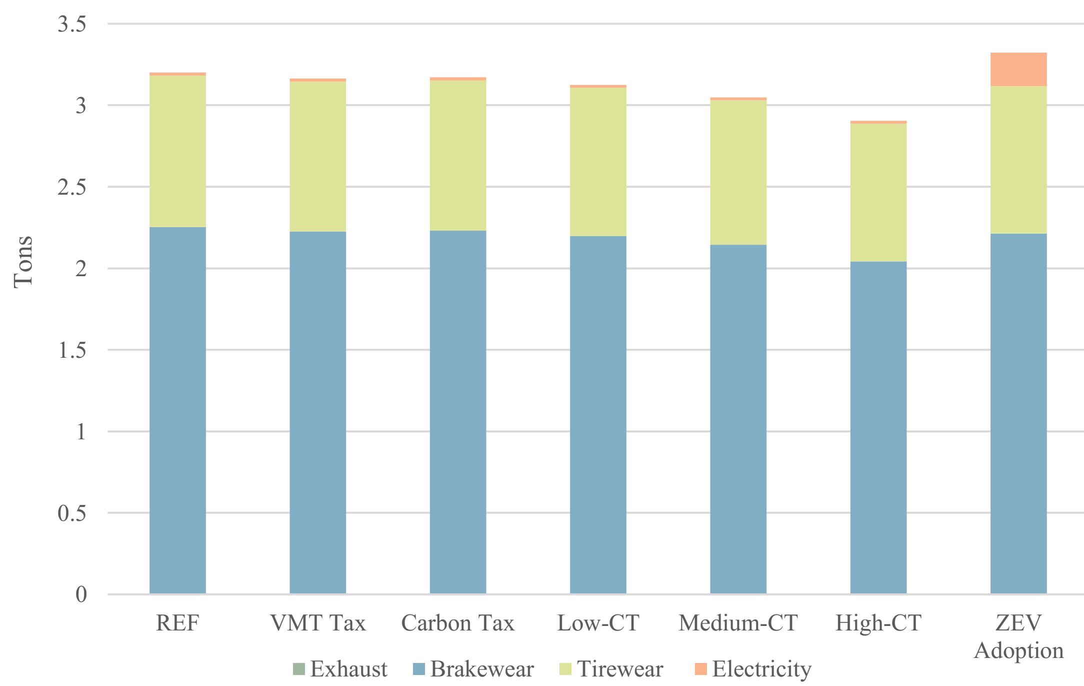


Figure 16. 2050 annual tons of PM 2.5 emissions by scenario and source.

Localized fine particulate matter emissions are directly produced from three aspects of vehicle operation: braking, tire use, and tailpipe exhaust emissions. When considering PM 2.5 produced from just these sources the High-CT pricing scenario demonstrated the greatest reductions in PM 2.5 emissions for both 2038 and 2050, followed by the Medium-CT pricing scenario and then the ZEV Adoption scenario (Figure 17).

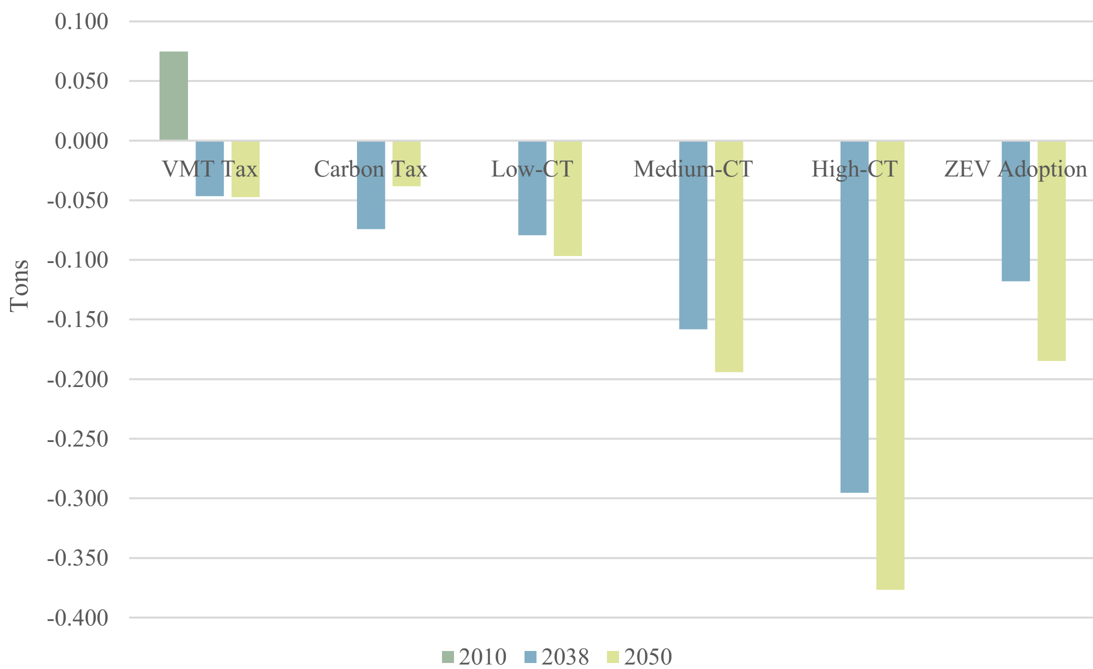


Figure 17. Avoided tons of PM 2.5 emissions from exhaust, brake wear, and tire use.

In the model results for each scenario the greatest reductions in PM 2.5 emissions are attributed to reductions from exhaust. The most drastic shift occurred between the 2010 and the 2038 model years. However, smaller reductions in exhaust emissions did occur from the 2038 to the 2050 model year.

As the assumptions in car engine technology projected cleaner, more fuel-efficient cars, the PM 2.5 exhaust emissions reduce greatly and emissions from tire and brake wear are a greater share of the total PM 2.5 emissions. For example, in the REF scenario in 2010 over 80% of direct emissions are produced from exhaust while in 2038 and 2050 approximately 50% of the PM 2.5 emissions were produced from exhaust, with the other half coming from tire and brake wear (Figure 18).

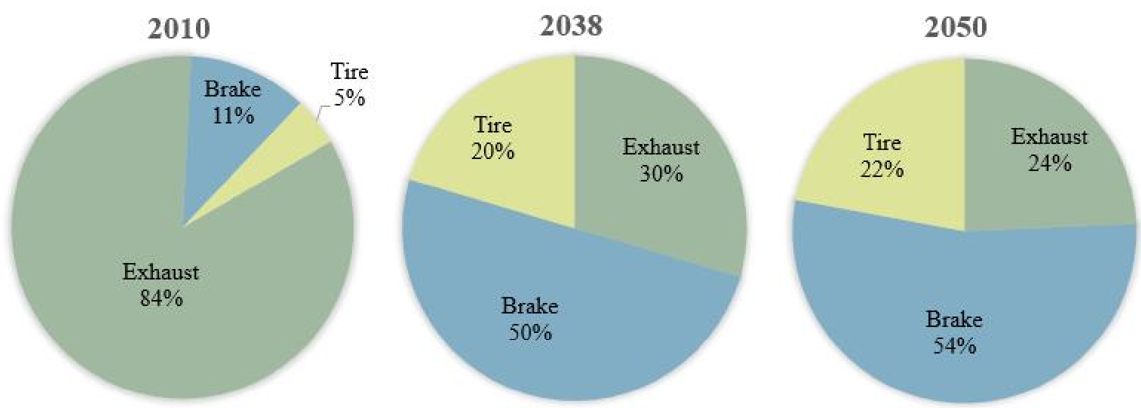
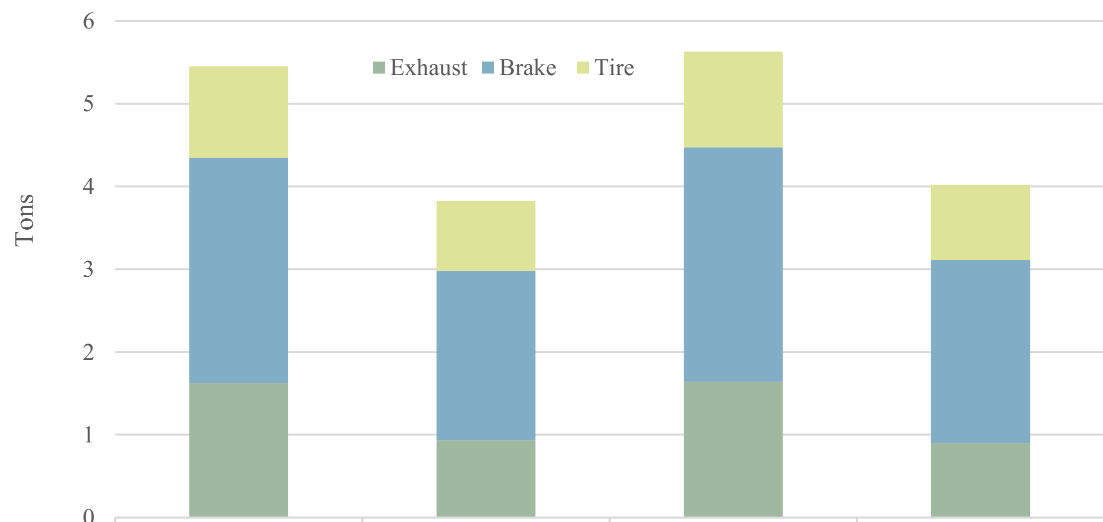


Figure 18. REF scenario PM 2.5 share of direct emissions attributed to exhaust, brake wear and tire use for 2010, 2038, and 2050.

Comparing the sources of direct PM 2.5 emissions for the ZEV Adoption scenario to the High-CT scenario (Figure 19) the High-CT scenario had lower emissions from brake and tire wear in both 2038 and 2050. However, the High-CT scenario had equivalent or slightly higher emissions from exhaust in both years.



	2038	2050	2038	2050
	High-CT		ZEV Adoption	
Tire	1.11	0.84	1.16	0.90
Brake	2.72	2.04	2.83	2.21
Exhaust	1.63	0.94	1.64	0.90

Figure 19. PM 2.5 emission from vehicles by source and year for the High-CT and ZEV Adoption Scenario.

VMT Responses to Policy

When modeling the different scenarios, one of the primary factors influencing emissions was the policy's impact on VMT. High pricing policies such as the Medium-CT and High-CT policies have the greatest influence on VMT in the model. This reflects the impact that increased travel costs have on driving habits. In 2038, the Medium-CT scenario resulted in a 5% reduction in VMT while the High-CT scenario resulted in a 9% reduction. All other scenarios demonstrated less than 1.5% reduction in VMT compared to the REF scenario in 2038. In 2050, the Medium-CT and High-CT demonstrated similar reductions in VMT (Figure 21). The ZEV Adoption scenario experienced slightly greater reductions in VMT than the Low-CT scenario, approximately 3.5% compared to the Low-CT scenario of 2.4% (Figure 20).

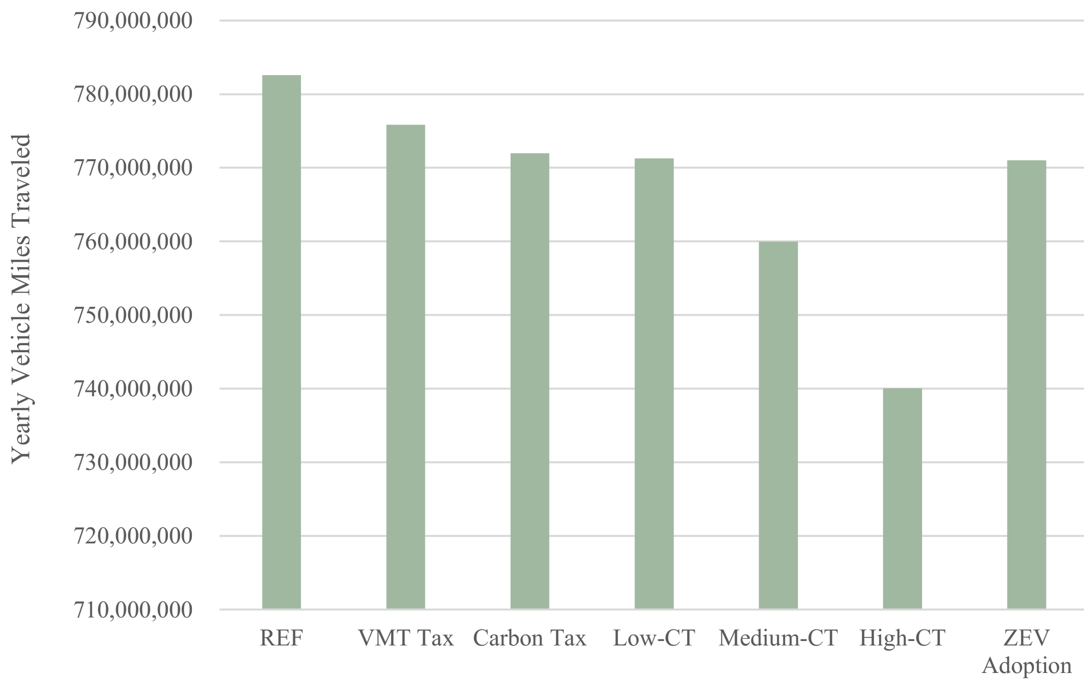


Figure 20. 2038 VMT by scenario.

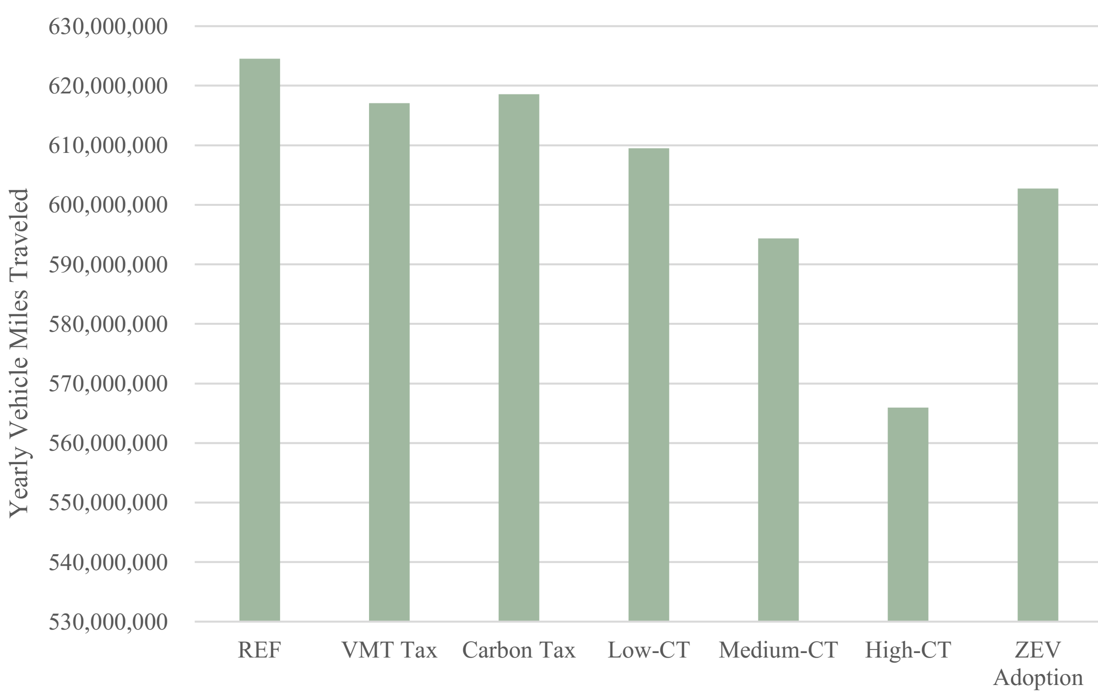


Figure 21. 2050 VMT by scenario.

Cumulative Emissions

Cumulative emissions based on a linear interpolation of emissions between modeled years reaffirmed results that the High-CT scenario achieved the greatest overall greenhouse gas and PM 2.5 emission reductions (Figure 22). The policy with the next greatest greenhouse gas reductions, when looked at cumulatively, was the ZEV Adoption policy. However, the policy with the next greatest cumulative PM 2.5 avoided emissions was the Medium-CT pricing scenario (Figure 23).

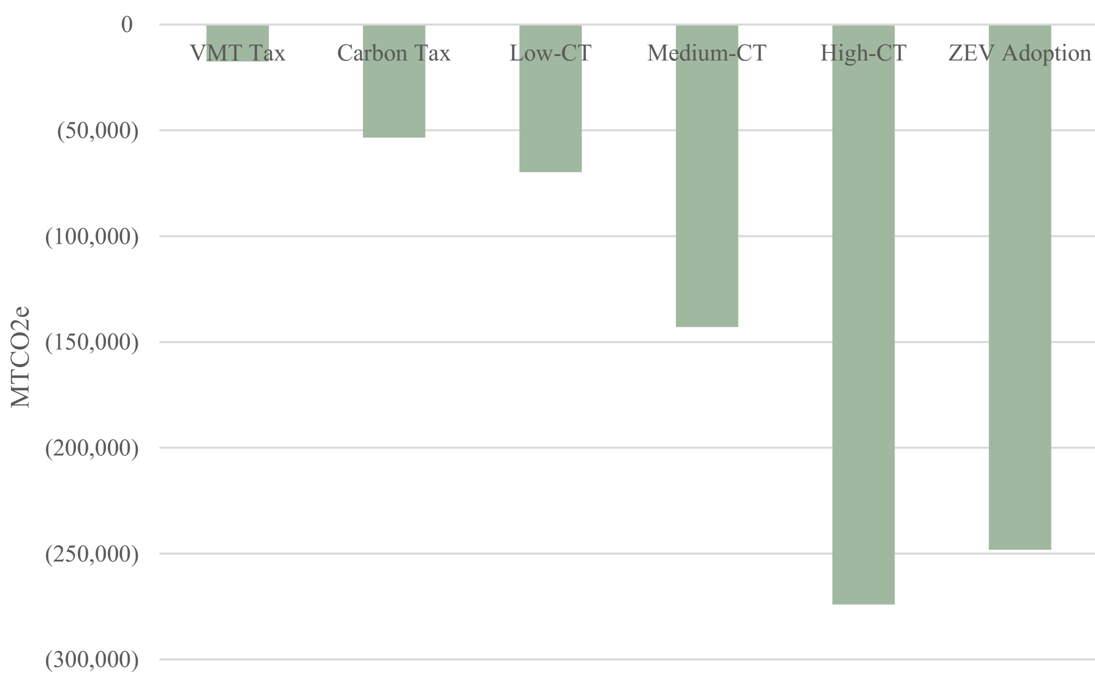


Figure 22. Cumulative avoided greenhouse gas emissions from 2010 through 2050 by scenario.

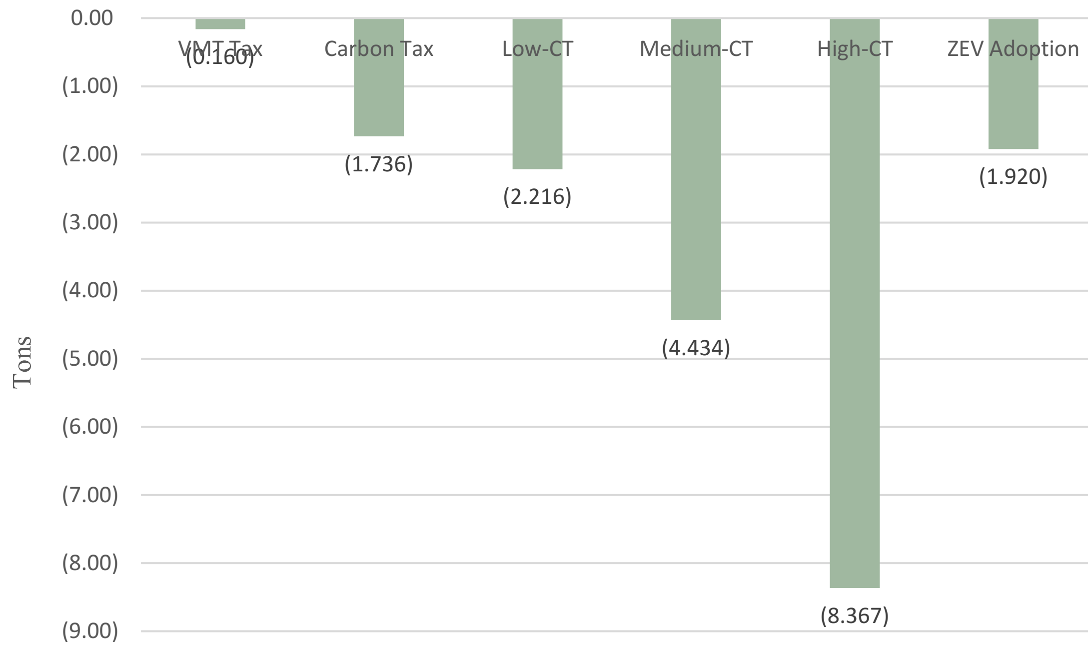


Figure 23. Cumulative PM 2.5 avoided emissions from 2010 through 2050 by scenario.

Economic Benefit Analysis

The economic benefit analysis results are presented as the net present value (NPV) of the monetized benefits in millions of 2019 dollars in Table 7. The results include the monetized health benefits of avoided PM 2.5, SCC, and any revenue generated from placing a price on carbon. Results are summed together to calculate a total potential benefit and presented with both a 3% and 5% discount rate. When the revenue from pricing carbon is included along with the economic benefits of reducing emissions the revenue generated dwarfed the other values, accounting for 98-99% of the overall NPV. Clearly, the modeled policies with emissions pricing components resulted in the greatest calculated benefit ranging from $111-649 million dollars.

Table 7. Net present value of policy benefits from 2010-2050.

	Avoided PM2.5 Health Benefit		Avoided GHG SCC Benefit		Carbon Pricing Revenue		Total Potential Benefit	
Discount Rate	3%	5%	3%	5%	3%	5%	3%	5%
VMT Tax	$ (0.07)	$ (0.13)	$ 0.43	$ 0.05	$ -	$ -	$ 0.36	$ (0.08)
Carbon Tax	$ 0.43	$ 0.28	$ 1.86	$ 0.40	$ 197.86	$ 130.84	$ 200.15	$ 131.52
Low-CT	$ 0.53	$ 0.33	$ 2.33	$ 0.49	$ 176.92	$ 110.53	$ 179.77	$ 111.36
Mid-CT	$ 1.06	$ 0.67	$ 4.65	$ 0.98	$ 320.78	$ 196.73	$ 326.49	$ 198.38
High-CT	$ 1.99	$ 1.26	$ 8.81	$ 1.85	$ 639.17	$ 400.74	$ 649.97	$ 403.84
ZEV Adoption	$ 0.50	$ 0.34	$ 7.85	$ 1.62	$ -	$ -	$ 8.35	$ 1.96

Monetized benefits of each scenario in millions of 2019 dollars presented with a 3% and 5% discount rate. Includes estimated values from avoided PM 2.5 emissions, avoided greenhouse gas emissions based on the SCC and revenue generated from carbon pricing and total potential benefit in net present value (NPV).

Looking specifically at the monetized benefit associated with avoided emissions, values ranged from negative $80,000 for the VMT Tax scenario to positive $10.79 million for the High-CT scenario. The negative range for the VMT Tax scenario is a result of increased emissions compared to the REF scenario for the first several years. The economic benefit results for avoided emissions are presented in Table 8 along with the total potential benefit in NPV of reducing those emissions.

Table 8. Net present value of health and SCC benefits 2010-2050.

	Avoided PM2.5 Health Benefit		Avoided GHG SCC Benefit		Total Potential Benefit	
Discount Rate	3%	5%	3%	5%	3%	5%
VMT Tax	$ (0.07)	$ (0.13)	$ 0.43	$ 0.05	$ 0.36	$ (0.08)
Carbon Tax	$ 0.43	$ 0.28	$ 1.86	$ 0.40	$ 2.29	$ 0.68
Low-CT	$ 0.53	$ 0.33	$ 2.33	$ 0.49	$ 2.85	$ 0.82
Mid-CT	$ 1.06	$ 0.67	$ 4.65	$ 0.98	$ 5.71	$ 1.65
High-CT	$ 1.99	$ 1.26	$ 8.81	$ 1.85	$ 10.80	$ 3.11
ZEV Adoption	$ 0.50	$ 0.34	$ 7.85	$ 1.62	$ 8.35	$ 1.96

Monetized benefits of avoided PM 2.5 and greenhouse gas emissions. Data calculated in millions of 2019 dollars and presented in NPV based on a 3% and 5% discount rate.

Chapter IV

Discussion

I hypothesized that the transportation-specific policy, the ZEV Adoption scenario, would result in the greatest health benefit based on the reduction in PM 2.5 emissions. However, the data indicated, that of the tested scenarios, the High-CT pricing scenario resulted in the greatest avoided emissions of PM 2.5 in both the 2038 and 2050 model years. This policy also resulted in the greatest reduction in cumulative emissions of both PM 2.5 and greenhouse gas emissions when assessed for the 2010-2050 time in Jackson County. It follows that the total NPV of the monetized benefit of PM 2.5 emission reductions for the High-CT scenario were the highest of all scenarios ranging from $1.2-1.9 million dollars, depending on the discount value used.

In regards to greenhouse gas emissions, the results for individual model years differed slightly from the PM 2.5 results. In 2038, the High-CT scenario resulted in the greatest reduction in greenhouse gas emissions. However, in 2050 the greatest reductions in greenhouse gas emissions were a result of the ZEV Adoption scenario. Looking at cumulative emissions the High-CT scenario produced the greatest reduction of emissions over the entire time period.

The research results indicate that VMT reduction may have a greater influence on co-benefits in future years by reducing direct emissions of PM 2.5 from tire and brake wear. This finding is only true if assumptions about vehicle engine technology improvements are true. The MOVES model adopted assumptions that engine technology improvements to the entire fleet would result in large reductions of PM 2.5 emissions from exhaust. Policies that reduce PM 2.5 emissions from exhaust have a greater impact in earlier years when PM 2.5 emissions are largely associated with the exhaust of the vehicle. In future years, policies that reduce VMT and thus emissions from brake wear and tire use are more impactful in avoiding PM 2.5 emissions. For this reason, in later years cap and trade pricing scenarios that encouraged reduced VMT resulted in greater reductions in PM 2.5 emissions than the ZEV Adoption scenario. The ZEV Adoption policy did not have the same influence on VMT as did the pricing scenarios, but does impact exhaust emissions.

Since a cap and trade program does not dictate a price on carbon, as does a carbon tax, the actual price per ton is subject to market influences. With that in mind, it may be more realistic to consider the range of prices (High-CT, Medium-CT and Low-CT) of the cap and trade scenarios. When comparing the modeled results of the Medium-CT and Low-CT to the ZEV Adoption scenario, the ZEV Adoption scenario resulted in greater reductions in greenhouse gas emissions for both model years and cumulatively. However, the ZEV Adoption policy resulted in slightly higher cumulative emissions of PM 2.5 when compared to the Medium-CT scenario and slightly lower PM 2.5 emissions than the Low-CT scenario. When the SCC and benefit per ton NPV are compared the ZEV Adoption scenario results indicate a higher monetized benefit based on avoided emissions than both of the Low-CT and Medium-CT pricing scenarios. If the cap and trade market prices remained at the low or medium projection a policy that increases zero-emission vehicles might result in equivalent or increased avoided emissions.

Looking at overall economic benefits, policies that priced carbon emissions clearly resulted in the greatest NPV estimates when compared to policies that did not price carbon. This is to be expected, and carbon-pricing revenue constitutes over 98% of the NPV benefit estimate for those carbon-pricing policies. Limiting the NPV assessment to health and SCC benefits resulting from the avoided PM 2.5 and greenhouse gas emissions, the High-CT pricing scenario demonstrated the greatest benefit ranging from $3.1-$10.7 million dollars, depending on the discount rate used.

Greenhouse gas policies will reduce local air pollutants in the transportation sector, but the extent to which they do depends on the type of policy implemented and the timing of that implementation. Based on the conclusions of this research, it is clear that policies that influence VMT reduce emissions of greenhouse gases and air pollutants in current and future years. However, as emissions from exhaust become less significant due to improved engine technology, policies that encourage less driving have a greater influence on PM 2.5 emissions by reducing emissions from brake use and tire wear.

Additional Applications

One of the aims of this research was to demonstrate a practical approach to modeling health impacts in the transportation sector that could be adapted for additional studies in air quality and climate mitigation policy analysis. The approach used in this research could be improved upon by utilizing the recently developed and updated version of RSPM, VisionEval. Additionally, EPA's MOVES model could be adapted and used to model more years of data, encompass a greater geographic area, review additional policies, include more vehicle types, be adjusted for speeds and congestion and model additional pollutants of concern. A more in-depth cost-benefit analysis would allow policy makers to include the impact of administrative costs associated with policy implementation, an assessment of road maintenance costs and impacts to economically vulnerable communities.

Research Limitations

One major influence on the results were policy assumptions inherent in both modeling tools. The RSPM model had assumptions on future driving habits impacting VMT and other outcomes, while the MOVES model included technology assumptions that resulted in reductions in PM 2.5 emissions from exhaust that ultimately impacted results. Additionally, due to constraints in the MOVES model the electricity portion of the plug-in hybrid vehicles was not accurately accounted for, and emission estimates may have been overestimated for those vehicle types, especially in the ZEV Adoption scenario.

The scope of this research was limiting in that the research only considered a single county, for three model years, and modeled only passenger cars and trucks. There may be greater health benefits when considering multiple vehicle types and geographic areas. For example, there may be greater impacts associated with heavy-duty fleet vehicles because these vehicles tend to produce more PM 2.5 than an average passenger car or truck. More frequent years of modeling would allow for refined results in regards to emissions estimates used in the benefit values and NPV estimates. The increased frequency may also provide insight into the timing of vehicle emission standard improvements.

Conclusions

There are pros and cons to each potential policy. Some allow for revenue generation while others decrease the emissions intensity of the fleet, allowing households to drive more while producing less emissions per mile. While a high carbon-pricing scenario resulted in the greatest reduction of emissions, there are questions about the willingness of decision makers to price carbon at that level.

It is clear that improvements to engine technology reduce exhaust emissions and play a significant role in achieving emission reduction goals. However, policies that dictate these types or improvements are often not least cost solutions and require large-scale market influence, typically not done at the state or local level.

As the fleet adopts more zero-emission vehicles, the significance of cleaner electricity sources increases so that emissions of both greenhouse gases and PM 2.5 are true reductions and not just displaced emissions. Additionally, reductions in VMT make valuable contributions to reducing greenhouse gas emissions and improving air quality. This research highlights the benefit and importance of implementing improvements to vehicle engine technology, transitioning to emission-free sources of electricity generation and reducing VMT.

Appendix 1

Emissions Data Results

Table 9. MOVES and electricity emissions results for 2010, 2038 & 2050.

Scenario	Units	2010	2038	2050
REF	MTCO2 Equivalent -Tailpipe exhaust	630,281	180,763	139,731
	MTCO2 Equivalent - Electricity	-	84	281
	Primary Exhaust PM2.5 - (Tons)	36.91	1.70	1.02
	Primary PM2.5 - Brake wear (Tons)	4.95	2.88	2.25
	Primary PM2.5 - Tire wear (Tons)	2.00	1.17	0.93
	PM 2.5 - Electricity (Tons)	-	0.00	0.02
VMT Tax	MTCO2 Equivalent -Tailpipe exhaust	631,796	179,306	138,156
	MTCO2 Equivalent - Electricity		84	278
	Primary Exhaust PM2.5 - (Tons)	36.97	1.69	1.01
	Primary PM2.5 - Brake wear (Tons)	4.96	2.85	2.22
	Primary PM2.5 - Tire wear (Tons)	2.00	1.16	0.92
	PM 2.5 - Electricity (Tons)	-	0.00	0.02
Carbon Tax	MTCO2 Equivalent -Tailpipe exhaust	630,281	178,345	138,417
	MTCO2 Equivalent - Electricity	-	83	279
	Primary Exhaust PM2.5 - (Tons)	36.91	1.68	1.01
	Primary PM2.5 - Brake wear (Tons)	4.95	2.84	2.23
	Primary PM2.5 - Tire wear (Tons)	2.00	1.16	0.92
	PM 2.5 - Electricity (Tons)	-	0.00	0.02
Low-CT	MTCO2 Equivalent -Tailpipe exhaust	630,281	178,184	136,413
	MTCO2 Equivalent - Electricity	-	83	275
	Primary Exhaust PM2.5 - (Tons)	36.91	1.68	1.00
	Primary PM2.5 - Brake wear (Tons)	4.95	2.83	2.20
	Primary PM2.5 - Tire wear (Tons)	2.00	1.16	0.91
	PM 2.5 - Electricity (Tons)	-	0.00	0.02

Medium-CT	MTCO2 Equivalent -Tailpipe exhaust	630,281	175,611	133,075
	MTCO2 Equivalent - Electricity	-	82	269
	Primary Exhaust PM2.5 - (Tons)	36.91	1.66	0.98
	Primary PM2.5 - Brake wear (Tons)	4.95	2.79	2.14
	Primary PM2.5 - Tire wear (Tons)	2.00	1.14	0.89
	PM 2.5 - Electricity (Tons)	-	0.00	0.02

High-CT	MTCO2 Equivalent -Tailpipe exhaust	630,281	171,090	126,825
	MTCO2 Equivalent - Electricity	-	80	257
	Primary Exhaust PM2.5 - (Tons)	36.91	1.63	0.94
	Primary PM2.5 - Brake wear (Tons)	4.95	2.72	2.04
	Primary PM2.5 - Tire wear (Tons)	2.00	1.11	0.84
	PM 2.5 - Electricity (Tons)	-	0.00	0.02

ZEV Adoption	MTCO2 Equivalent -Tailpipe exhaust	630,281	172,285	121,565
	MTCO2 Equivalent - Electricity	-	1,000	3,000
	Primary Exhaust PM2.5 - (Tons)	36.91	1.64	0.90
	Primary PM2.5 - Brake wear (Tons)	4.95	2.83	2.21
	Primary PM2.5 - Tire wear (Tons)	2.00	1.16	0.90
	PM 2.5 - Electricity (Tons)	-	0.02	0.21

Table 10. 2038 PM 2.5 emissions from electricity generation calculated data.

Scenario	Total KWh needed to power EVs in 2038	Share of KWh generated by natural gas combustion (8% of total)	Amount of natural gas combusted to generate estimated KWh (Million BTU)	Pounds of PM 2.5 emissions	Tons of PM 2.5 emissions
REF	844,658	67,573	529	3.94	0.00
VMT Tax	836,884	66,951	524	3.90	0.00
Carbon Tax	833,909	66,713	522	3.89	0.00
Low-CT	833,189	66,655	521	3.88	0.00
Medium-CT	821,710	65,737	514	3.83	0.00
High-CT	801,400	64,112	501	3.74	0.00
ZEV Adoption	10,006,358	800,509	6,262	46.65	0.02

Table 11. 2050 PM 2.5 emissions from electricity generation calculated data.

Scenario	Total KWh needed to power EVs in 2050	Share of KWh generated by natural gas combustion (30%)	Amount of natural gas combusted to generate estimated KWh (Million BTU)	Pounds of PM 2.5 emissions	Tons of PM 2.5 emissions
REF	2,205,057	661,517	5,174	38.55	0.02
VMT Tax	2,177,260	653,178	5,109	38.07	0.02
Carbon Tax	2,186,123	655,837	5,130	38.22	0.02
Low-CT	2,156,948	647,085	5,061	37.71	0.02
Medium-CT	2,107,431	632,229	4,945	36.85	0.02
High-CT	2,015,133	604,540	4,729	35.23	0.02
ZEV Adoption	23,530,309	7,059,093	55,216	411.41	0.21

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