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In this dissertation, I evaluate the health effects of the automobile (or vehicle) fuel economy. Automobile fuel economy is regulated by the Corporate Average Fuel Economy (CAFE) standards put into effect in 1975 in the United States primarily to reduce the oil consumption and dependency on oil import in response to the Oil Embargo in the 1970s. The health benefit was not thoroughly analyzed in policy analyses of CAFE standards. I hypothesize that better automobile fuel economy results in less mobile source air pollutants such as fine Particulate Matters ($PM_{2.5}$), Carbon Monoxide (CO), and Nitrogen Dioxide (NO_2), and hence improves air quality, which in turn reduces air pollutant related diseases such as asthma. Thus, CAFE standards have health benefits because CAFE standards increase the on-road vehicle fleet fuel economy.

I seek empirical evidence of the health effects of automobile fuel economy through the improvement of air quality. Using vehicle registration and fuel consumption data, air pollutant data, health survey data, and other relevant data in the United States, I apply statistical mediation analysis techniques to assess the variation of asthma with respect to the changes of automobile fuel economy over time through the air pollutants mechanism. The empirical analysis results, under certain assumptions and with some limitation due to the data, support my key hypotheses: 1) there is a clear negative correlation between the automobile fuel economy and mobile source air pollutants over time; 2) there is a negative correlation between the fuel economy and asthma prevalence through the air

pollutants mechanism; 3) empirical evidence supports that the air pollutants are the mediators through which automobile fuel economy affects health.

This dissertation provides the empirical evidence of the health effects of automobile fuel economy improvement through improvements in air quality. It contributes to the literature and knowledge to the research community in two aspects: first, by identifying the health benefits of automobile fuel economy and an additional support to tighten the automobile fuel economy standards; second, by applying statistical mediation methods in econometric analysis.

THE HEALTH EFFECTS OF AUTOMOBILE FUEL ECONOMY THROUGH IMPROVEMENTS IN AIR QUALITY

by

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Approved by

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APPROVAL PAGE

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CHAPTER I

INTRODUCTION

Automobiles are one of the most important means of transportation around the world. However, automobile driving imposes externalities to society. Parry and others (2007) summarize and categorize the externalities associated with automobile use. The most influential externality, owing to its detrimental health effects, is air pollution that the pollutants emit into the air from the emissions of fuel combustion in vehicle engines[1]. Unless otherwise described, my dissertation limits its focus on air pollution of automobiles (or mobile source air pollution, or air pollution of transportation). In the rest of the dissertation, I use ***the air pollution*** to denote specifically the air pollution of automobiles.

Regulations on the air pollution focus mainly on emission and fuel economy standards. Effectively, emission standards are to reduce the air pollution by controlling air pollutants per unit of fuel consumption, and fuel economy standards are to reduce the air pollution by controlling fuel consumption per unit of distance driven. Meanwhile, because emission standards play significant roles in reducing air pollution, they are also

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[1] The other externalities are: global warming caused by carbon dioxide (CO_2) which is the main output of fuel combustion, foreign oil dependency that compromises national security and foreign policies, traffic congestion and time loss, traffic accidents and their social costs, noise, parking subsidies, damage to highways, highway maintenance costs, urban sprawl, parking, and the environmental impacts of disposing vehicles and parts, etc.

substantially reviewed and discussed in this dissertation. My dissertation examines the health effects of Vehicle Fuel Economy, and the mechanism through the reduction of automobile air pollutants. In particular, I seek the empirical evidence of correlation between Vehicle Fuel Economy and health outcomes through air pollutants by using data on vehicle miles, fuel sales, air pollutants, and asthma incidence.[2] I formulate the empirical estimations in a framework of statistical mediation effect under a series of structural equation models.

There is a lot of research and literature on the health effects of vehicle emission standards. However, few have studied the health outcome attributed to vehicle fuel economy standards[3] along with the enactment of the emission standards. Neither have the policy makers focused on the health benefits from vehicle fuel economy standards. Although recently the US Department of Transportation National Highway Traffic Safety Administration (USDOT NHTSA) does mention the health benefits from fuel efficiency in their Regulatory Impact Analysis (RIA) for CAFE standards, they provide no empirical evidence there.[4] The innovations of my dissertation are in two aspects: establishing numerically the correlation between the fuel economy of automobiles and

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[2] I choose modeling effects of fuel economy instead of CAFE standards because the CAFE standards affect only new automobiles but not the automobiles sold before the standards taken into effect. Assuming the auto industry is compliant to the standard, the average on-road vehicle fuel economy will be improved due to new higher fuel economy automobiles being put onto the road.

[3] As of March 1st, 2017, searching at Google.com, Google Scholar and EBSCO database with keywords Fuel Economy and health returned no relevant literature.

[4] US EPA and NHTSA, Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles - Phase 2, Regulatory Impact Analysis, Final Rule. August 2016, EPA-420-R-16-900.

health outcomes, in particular asthma; and determining and quantifying the mechanism of such correlation through the reduction of air pollution.

The dissertation is organized as follows. Chapter II describes the air pollution from automobiles and the characteristics of each pollutants, Chapter III articulates the institutional background and legal regulations, Chapter IV reviews the research and literature, Chapter V prescribes the hypotheses and empirical estimation framework, Chapter VI outlines the data used for the empirical analysis, Chapter VII summarizes the data variables and presents them in graphics, Chapter VIII specifies econometric models and presents the estimation results, Chapter IX interprets results and gives policy implications, and finally Chapter X concludes the findings

.

CHAPTER II

AIR POLLUTION FROM AUTOMOBILES: DESCRIPTION AND HEALTH EFFECTS

If motor fuel is pure and completely combusted in motor engines, only carbon dioxide (CO_2) and water (in steam form) will be generated. They impose little direct health hazard to lives. However, fuel is neither pure nor combusted perfectly in vehicle engines. Incomplete combustion generates many by-products that are pollutants. These pollutants, resembling the pollutants from industrial manufacturing, impose adverse health impacts on human beings. The adverse health outcomes are associated with large costs, too. Section 2.1 describes these air pollutants in detail, section 2.2 reviews these adverse health outcomes and the costs associated with them, section 2.3 discusses other externalities.

2.1 Description of Pollutants

Pollutants from automobile emissions are broken down into exhaust emissions from the tailpipe and evaporative emissions from the hood (Mathur and Garg 1991, Faiz, Weaver et al. 1996). They consist of, but are not limited to, hydrocarbons, carbon monoxide, nitrogen oxides and nitrous oxide, sulfur oxides, particulate matter, volatile organic compounds, and carbon dioxide. The United States Environmental Protection

Agency (EPA) added carbon dioxide, one of the greenhouse gases (GHGs), to the list of pollutant to regulate due to its devastating climate effect (global warming) on December 15, 2009.

Different pollutants have different regulatory standards because their physical and chemical characteristics, costs to implement control, harmfulness to health, and composition in the emissions are different. In the follow paragraphs, I describe the physical and chemical characteristics of the above pollutants[5].

Hydrocarbons (HCs) are organic compounds that contain only carbon and hydrogen. They are straight chain, branched chain, or cyclic molecules. HCs from vehicle emissions are unburned or partially burned fuel. They are essentially raw fuel. The majority of the HC emissions come from improper engine ignition timing, defective ignition components, unmetered air entering the intake manifold and ultimately the combustion chambers, defective catalytic converters, defective air injection components, or low cylinder compression.

Carbon monoxide (CO) is a molecule that consists of one carbon atom and one oxygen atom connected by a triple covalent bond. CO is a colorless, odorless, and tasteless gas that is slightly less dense than air. CO is a by-product of incomplete combustion that results in partial oxidation of motor fuel. CO is emitted directly from vehicle tailpipes.

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[5] The information of pollutants is based on the US EPA air pollutant website http://www3.epa.gov/air/airpollutants.html, and WHO air pollution website http://www.who.int/topics/air_pollution/en/.

Nitrogen oxides (NO_x) are a mixture of nitric oxide (or nitrogen monoxide, NO), nitrogen dioxide (NO_2), and nitrate (NO_3). They are produced during combustion of motor fuels in automobile engines, with an excess being created when more air (containing the nitrogen gas) is present, or the temperatures are higher, than needed for efficient and complete combustion of the fuel. Chemically, NO is a colorless gas, which is the major component of smog. NO can be oxidized in air to form NO_2. NO_2 is a brown toxic gas with a sharp and biting odor. NO_3 is formed from the reaction of NO_2 and ozone (O_3). However, this reaction works mainly at night, and NO_3 photolyses rapidly towards NO_2 at dawn. NO_3 does not usually cause health problems because of its transient existence. NO_x gases react to form smog and acid rain, and are central to the formation of ground level ozone. Ozone can damage lung tissue and reduce lung function mostly in susceptible populations such as children, elders and asthmatics. Meanwhile, NO_x reacts with ammonia, moisture, and other compounds to form nitric acid vapor and related particles such as the fine particulate matters of $PM_{2.5}$ (Refer to Particulate Matters in this section for detail). Note that NO_x does not include N_2O.

Nitrous oxide (N_2O) is a colorless, non-flammable gas with a slightly sweet odor and taste. N_2O is widely used in surgery and dentistry as an anesthetic. N_2O can give rise to nitric oxide (NO) in reaction with oxygen atoms. At normal environmental concentrations, nitrous oxide is not harmful to humans. However, N_2O is one of the Green House Gases (GHGs) that contributes to global warming. It has a high "global warming potential" (some 300 times that of CO_2). Moreover, N_2O also damages the ozone layer, thus reducing the protection offered from harmful UV sun rays.

Sulfur oxides (SO_x) are compounds of sulfur and oxygen molecules. SO_x refer to Sulfur monoxide (SO), Sulfur dioxide (SO_2), Sulfur trioxide (SO_3), sulfur tetroxides (SO_4), disulfur monoxide (S_2O), and disulfur dioxide (S_2O_2). Most of them are colorless gases with a pungent and irritating odor and taste. SO_x is emitted from engines burning fuel containing sulfur. Sulfur dioxide (SO_2) and sulfur trioxide (SO_3) are the main components of the pollutant SO_x. SO_2 is highly soluble in water: forming weakly acidic sulfurous acid. SO_2 forms SO_3 when it reacts with oxygen (O_2) in the air. SO_3 rapidly combines with water to produce sulfuric acid. This causes the acid rain. Moreover, SO_x gases may combine with smog to form particulate matters. Note that SO_x does not include the lower sulfur oxides (eg. S_nO, S_7O_2 and S_6O_2).

Particulate Matter (PM) is the term for solid particles and liquid droplets suspended in the air. Some of them are large enough to be visible in smog, some are small (fine PM). Particulate matter can be emitted directly or be formed in the atmosphere from gaseous pollutants (such as SO_2 and NO_x reacting to form fine particles). Particles emitted directly into the air are called direct or primary PM. Particles are formed indirectly in the atmosphere from the chemical reaction of gaseous pollutants (termed precursors). These particles consist of a wide variety of sizes. They have been historically assessed based on size, typically measured by the diameter of the particle in micrometers. PM_{10} and $PM_{2.5}$ are the two most frequently used terms of PM. PM_{10} refers to particles that are 10 micrometers in diameter or less (about 1/7 of a human hair's diameter). $PM_{2.5}$, also named fine PM, refers to particles that are 2.5 micrometers in diameter or less. These small particles can penetrate deeply into sensitive lung tissue and damage it. In extreme cases, it can cause premature death. Inhalation of such particles may cause or worsen respiratory diseases, such as emphysema or bronchitis, or may also aggravate existing heart disease. Automobiles emit direct PM from their tailpipes and from normal brake and tire wear. Precursors in vehicle exhaust may react in the atmosphere to form indirect PM. These precursors are nitrogen oxides (NO_x), volatile organic compounds (VOCs), and additionally for forming $PM_{2.5}$, sulfur oxides (SO_x) and ammonia (NH_3).

Volatile organic compounds (VOCs) are a large group of organic compounds that have a boiling point less than or equal to 250 °C. Unlike the other pollutants, VOCs mainly come from evaporative emissions although they are also found in tailpipe emission. Studies have found more than 50 individual VOCs from vehicle emissions. The most abundant ones are ethane, isopentane, acetylene, toluene and n-butane. Vehicular VOCs come from the vehicle interior materials,[6] running engine evaporations,[7] and fuel vapors.[8] In the presence of sunlight, VOCs and nitrogen oxides react to produce ground-level ozone and other compounds. This contributes to the smog-related pollution.

Carbon Dioxide (CO_2), the fully oxidized form of carbon, is one of the metabolic gases that human and animal breathe out. It is also one of the key components that make up the atmosphere keeping the earth warm. Energy arrives from the sun in the form of visible light and ultraviolet radiation. The earth emits some of this energy as infra-red

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[6] These materials include hard plastics, elastomers, rubber, natural or synthetic leather, fabrics and fibers.

[7] The evaporations include the release of gasoline vapors resulting from diurnal temperature variations, "hot soak" running losses, and resting losses

[8] These vapors are those escaping either from the fuel system or while the vehicle is being refueled

radiation. CO_2 “blocks” the infra-red light by reflecting a portion of it back thus keeping the portion of heat from sunlight around the earth. However, elevated CO_2 levels in the atmosphere keeps more heat around the earth, thus causing the so called greenhouse effects lead to global warming. CO_2 can be absorbed by plants during photosynthesis and leading to the release of oxygen. Unfortunately, both industrial product manufacturing and vehicle driving emit CO_2. Thus, controlling CO_2 emission requires regulation on both sources.

2.2 Detrimental Health Effects

There is a large body of literature documenting the detrimental health outcome of air pollutants. In general, as summarized by WHO (WHO/Europe 2013) and US EPA[9], respectively, people exposed to toxic air pollutants have an elevated risk of getting cancer or experiencing other serious health effects, including damage to the immune system, neurological, reproductive (e.g. reduced fertility), developmental, respiratory system, and other health problems. Air pollution is a main culprit of many respiratory diseases such as asthma and Chronic Obstacle Pulmonary Disease (COPD).

Among the emissions, HCs are a particular problem. Unburned or partially burned fuel react in the presence of nitrogen oxides and sunlight to form ground-level ozone, a major component of smog. Ozone irritates the eyes, damages the lungs, and aggravates

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[9] For details, refer to *Risk Assessment for Toxic Air Pollutants: A Citizen's Guide*, EPA publication 450/3-90-024, 1991

respiratory problems. Prolonged exposure to HCs increases the risk of having asthma, liver disease, lung disease, and cancer.

CO enters the bloodstream through the lungs and forms carboxyhemoglobin, reducing the blood's ability to carry oxygen. Overexposure to CO may be life threatening (ie. carbon monoxide poisoning). Because CO reduces the flow of oxygen in the bloodstream, it is particularly dangerous to those with heart disease.

PMs have adverse health effects on breathing and respiratory systems. They can cause damage to lung tissue, cancer, and premature death. The elderly, children, and people with chronic lung disease, influenza, or asthma are especially sensitive to the effects of particulate matters. The fine PMs are particularly harmful because of their ability to reach the lower regions of the respiratory tract. Many scientific studies have linked breathing PM to a series of significant health problems, including aggravated asthma, respiratory symptoms like coughing and difficult or painful breathing, chronic bronchitis, decreased lung function, and premature death. Certain people, such as older adults, children, and those with existing respiratory problems may have a higher risk for PM-related health effects. Short-term exposure can aggravate lung disease, cause asthma attacks and acute bronchitis, and may also increase susceptibility to respiratory infections. Long-term exposure has been linked to reduced lung function and the development of chronic bronchitis.

The health effects of volatile organic compounds (VOCs) will depend on the nature of the VOC, the level of exposure, and the length of exposure. Long-term exposure to volatile organic compounds can cause damage to the liver, kidneys, and central nervous system. Short-term exposure to VOCs can cause eye and respiratory tract irritation, headaches, dizziness, visual disorders, fatigue, loss of coordination, allergic skin reactions, nausea, and memory impairment. Particularly, compounds of VOCs such as benzene, formaldehyde, perchloroethylene, styrene, and toluene are considered carcinogens.

CO_2 generally imposes no harm to human health. In fact, it is naturally present in the atmosphere of the earth, and is a component of gas that human being and other organisms breathe out. There is a scientific consensus that climate change (warming) is occurring globally. In the past decades, studies have shown that CO_2 is the primary source of greenhouse gas that is responsible for global warming. Scientists from many disciplines ascertain that global warming will have devastating natural and social effects in the future if we do not control the CO_2 emission from now on. Global warming may affect animals' living, farming, fishery and agriculture. It may cause natural catastrophes, too. Such devastating catastrophes include ice melting from the polar poles that will raise the ocean level and immerse many coastal cities, animals changing migration patterns, plants changing the rhythms of sprouting, flowering, and fructifying affecting agricultural yields, and extreme weather conditions, etc. The EPA decided to classify rising CO_2 emissions as a hazard to human health in 2009 due to the global warming effects potentially threatening the lives of human beings.

Outdoor air pollution kills more than three million people across the world every year. Mobile source air pollution claims 50% of the death caused by air pollution in OECD countries. Over the five-year period from 2005 to 2010, there was an overall increase of about 4% in the number of premature deaths globally caused by outdoor air pollution – with an improvement in the OECD world being offset by a larger deterioration in the rest of the world. The number of deaths due to outdoor air pollution fell by about 4% in OECD countries between 2005 and 2010, while the number of years of life lost fell even further. However, while 20 of the 34 OECD countries achieved progress, 14 did not. The number of deaths due to outdoor air pollution in China rose by about 5%, although years of life lost increased by only about 0.5%. China has arguably succeeded in slowing the increase in the effect of air pollution on health, since a reduction in exposure to pollution will have a greater effect on years of life lost than on the number of deaths. India registered an increase of about 12% in the number of deaths and about 3% in years of life lost. Although the number of deaths in India is only just over half the number in China, the trend in India is increasing at a faster rate.

Air pollution can cause many health problems from asthma to heart disease, and even results in death. Researchers have explored the cost of air pollution, estimating that air pollution costs the Organization for Economic Co-operation and Development (OECD) countries, China, and India about 3.5 trillion US dollars a year in terms of the value of lives lost and illness with an increasing trend of such cost. In OECD countries, road transportation is likely responsible for about half of total cost (1.7 trillion US dollars), or about 1 trillion US dollars(OECD 2014).

Lave and Seskin (1970) evaluate the health cost of air pollution after established quantitative estimation frameworks on the effect of air pollution on various diseases.

They conclude that from $1.52 to $3 billion[10] per year would be saved for treating bronchitis, about $202 million would be saved for treating lung cancer, about $7.4 billion would be saved for treating all respiratory diseases, and about $2.86 billion per year would be saved for treating cardiovascular disease from a 50% abatement of air pollution in the major urban areas in the US. Carpenter et al. (1979) study whether exposure to air pollution incurs higher hospital utilization rates and additional treatment costs. Their results show that hospitalization rates, length of stay, and costs of respiratory and suspect circulatory system diseases were significantly greater among populations residing in the more polluted zones of the studied county. They estimate that the total increased cost for the 1.6 million people in the county is $32 million ($29.7 million for increased hospitalization rates and $2.3 million for increased length of stay).

The EPA claims that the total national cost in 1968 of damage resulting from air pollution was $109.7 billion, which includes $35.4 billion for residential property, $32 billion for materials, $41.6 billion for health, and $680 million for vegetation[11]. Meanwhile, the EPA conducted a survey of 23 studies published between 1967 and 1977 and finds that the estimated nationwide health costs of air pollution range from a few hundred to over sixty billion dollars per year.[12]

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[10] All monetary values in US dollar are converted to 2016 dollars. Conversion is done on the CPI Inflation Calculator at the US Bureau of Labor Statistics, http://www.bls.gov/data/inflation_calculator.htm. Numbers are rounded to the first decimal.

[11] Cost of Air Pollution Damage: A Status Report, final report 02/01/1973 of the EPA National Center for Environmental Economic

[12] The Health Costs of Air Pollution: A Survey of Studies Published between 1967 and 1977, draft report 09/23/1977 of the EPA National Center for Environmental Economic.

For motor vehicle related air pollution, Small and Kazimi (1995) estimate air pollution costs from various types of motor vehicles in the Los Angeles region. They find that the air pollution cost of the average car on the road in California in 1992 is $0.05 per mile, falling to half that amount in the year 2000. McCubinn and Delucchi (1999) conduct a systematic estimation on the health cost of vehicle related pollutants on various diseases. Besides have similar results to what Small and Kazimi have, they present the cost of CO, NO_x, PM, VOC, PMs and SO_2 on headaches, hospitalization, mortality, asthma attacks, eye irritations, lower and upper respiratory illnesses, chronic illness, etc. For example, the estimated total US national medical cost from all vehicle related pollutants was between $99.2 and $1219.7 billion in 1990.

More recently, Kan and Chen (2004) assess the economic cost of particulate air pollution in the urban areas of Shanghai, China. They estimate that the total economic cost of health impacts due to particulate air pollution in urban areas of Shanghai in 2001 was approximately 837.3 million US dollars, accounting for 1.03% of gross domestic product of the city. Bell et al. (2006) investigate the pollution health consequences of modest changes in fossil fuel use for three case study cities in Latin American: Mexico City, Mexico; Santiago, Chile; and São Paulo, Brazil. They argue that the air pollution control policy would have vast health benefits for each of the three cities, and the economic value of the avoided health impacts is roughly 24.7 to 194 billion US dollars.

CHAPTER III

INSTITUTIONAL BACKGROUND AND LEGAL REGULATIONS

Economic solutions seek for eliminating or at least cutting down pollutants and/or externalities to a social optimal level. Since pollutants impair health, eliminating or reducing pollutants that have deleterious health effects will provide health and social benefits.[13] There are many economic solutions to control the air pollutants and other externalities. Among them, the most cited are Pigovian tax and Cap-and-Trade approaches, whereas intensity standards are practical in many applications. This chapter is organized as the following: section 3.1 briefly summarizes the economic solutions for emission control, and sections 3.2 and 3.3 describe the history of emission standards, and fuel economy standards, respectively, in the US and other countries.

3.1 Economic Solutions

In environmental economics, the two most efficient solutions to internalize the externalities are Pigouvian tax and Cap-and-Trade policy. The former is a price control, and the latter is a quantity control. Theoretically, these two policy instruments are equivalent under competitive market with full information or some degrees of uncertainty (Weitzman 1974). However, in most countries the prevailing economic instruments are emission controls (to regulate the per unit pollutants) and fuel economy standards (to

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[13] Refer to Chapter II for the detrimental health effects of air pollutants.

regulate the per unit consumption of fuel). They are theoretically the less efficient intensity standards regulating emissions per unit of output.

3.1.1 Pigouvian Tax

In microeconomic theory, the best (i.e. efficient) economic solution to internalize (negative) externalities is to charge the party causing these externalities a marginal cost (price of the externality) equal to their marginal damage to society (the Pigouvian tax)[14]. A simplified illustration of this approach is shown in Figure 3.1, a typical Price-Quantity (P-Q) plot describing the supply and demand of a good that has negative externality. In the figure, the line D represents the demand for the good. The line MC represents the private marginal cost of producing the good. The line SMC is the social marginal cost of the good which is greater than the private marginal cost by the additional the cost of damage to society. Without any intervention, the equilibrium quantity q is larger than the social optimal equilibrium quantity q^*. The vertical distance between O and C (OC) is the cost of marginal damage to society and is the amount of Pigouvian tax at quantity q. Hence adding a Pigovian tax equals to the cost of marginal damage in the price of the product will shift the MC to the left of the P-Q plot and reach the SMC. Therefore, a socially optimal equilibrium quantity q^* ($q^* < q$) will be attained. A Lesser quantity of goods consumed means less pollution imposed on society.

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[14] Arthur Pigou (1920) details the mathematical analysis in his book *The Economics of Welfare*.

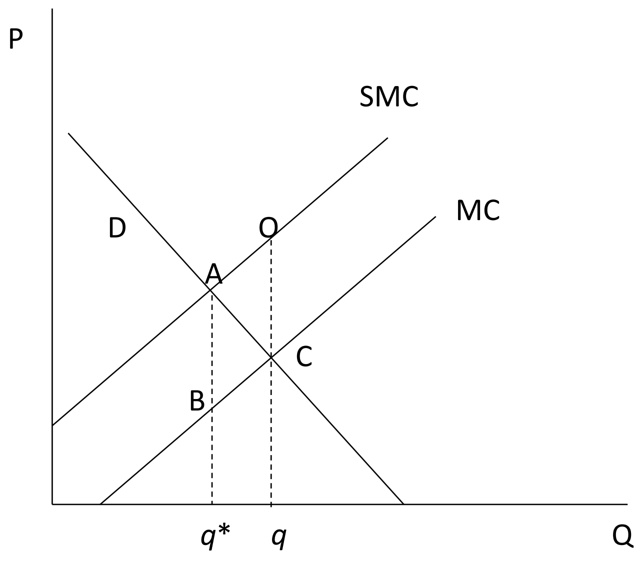

Figure 3.1 Illustration of the Pigouvian Solution to Reduce Pollution

Thus, it is most efficient to charge (or tax) drivers for their damages of air pollution to society. However, this approach requires a precise measurement of vehicle emissions and an estimation of the social costs of the air pollution in a monetary amount, and an institutional setting to effectively collect the costs of damage. Today, directly measuring a vehicle's emission is still technically infeasible and/or very costly (Fullerton and West 2010). Moreover, it is extremely difficult to precisely calculate the social cost of the air pollution, and it is costly (if possible) to enforce the taxation, not to mention the political difficulty in raising taxes (Sterner and Coria 2013). In the US, there is no taxation of vehicle emissions levied on the consumers' (vehicle owners') side. However, in many states, vehicles are required to perform annual emission inspections in order to renew their registration of license plates.

3.1.2 Cap-and-Trade Policy

Another possible solution is the Cap-and-Trade approach that is used in US and European countries in regulating the emissions from manufacturing plants and other sources. The approach sets a maximum amount of emissions per compliance period (the cap) in order to achieve a desired environmental effect, for all emitters under the program. Authorizations to emit in the form of emission allowances (permits) are allocated to the emitters, and the total number of allowances cannot exceed the cap. Individual control requirements are not specified for the emitters; instead, the emitters report all emissions and then surrender the equivalent number of allowances at the end of the compliance period. Permit trading enables the emitters to design their own compliance strategy based on their individual circumstances while still achieving the overall emissions reductions set by the cap. A less polluted emitter can trade their spare permits to the more polluted emitters, creating an incentive (reduction in the cost of operation) for an emitter to emit less. Carlson (2012) details the cap-and-trade policy in the application of regulating greenhouse gases (GHGs). The optimal policy is to set the cap of the pollutants at the level corresponding to q^*, the social optimum quantity of consumption of goods as illustrated in Figure 3.1, and allocate to the emitters. In this setting, the cap-and-trade policy achieves the same efficiency as Pigouvian tax.

However, applying this emission control approach to automobiles requires a clear target on the kind of pollutants, a precise measurement of pollutant at the social optimal consumption of goods, a well-run exchange market for the emissions, and tremendous efforts to ensure all drivers participate. Because there are millions of drivers in a country or around the world, maintaining such a trade market and enforcing the participation are very costly, not to mentioned the technical difficulties and feasibility in issuing myriads permits to millions of drivers. Cap-and-Trade may only be feasible to impose on fuel retailers. Today, there is no Cap-and-Trade policy on mobile source pollutants.

3.1.3 Intensity Standard and Fuel Economy Standards

Besides the above two policy instruments, the more practical but inefficient intensity standards are poplar in regulating the emission outputs. An intensity standard regulates an externality by setting a limit per unit of output. The emission control standards (limit at gram of pollutants per vehicle distance travel) and fuel economy standards (limit at gram of carbon per vehicle distance travel) are two examples of the intensity standard policies. Holland (2009) gives a theoretical and mathematical analysis of the intensity standards compared to Pigouvian solution and Cap-and-Trade approach[15]. Though intensity standards are not the first best policy instrument, emissions tax (Pigouvian solution) may be dominated by an intensity standard in the presence of incomplete regulation[16] (leakage) or market power. With complete regulation, combined intensity standards and consumption tax can even attain the first best. The stronger result holds that under certain conditions any tax or any emissions cap is dominated by an intensity standard. This provides the justification of applying intensity standards in environmental control policies.

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[15] The pollutant is modeled as an input to the production of consumption good in the analysis

[16] For example, different level of standards among different geographic or institutional regions

Because of the infeasibility of implementing Pigouvian solutions or Cap-and-Trade policies, the intensity standards of vehicle pollution control policies are implemented in most countries (Sallee 2010). In the United States, automobile fuel economy standards (the average fuel economy of new vehicle fleets) and emission standards (an automobile must meet in order to register to use) are the two major policy instruments to correct automobile air pollution externalities. Other countries such as European countries, China, and Japan also have adopted similar regulations.

In analog to Holland (2009), an emission standard is an intensity standard to regulate the vehicular pollutant. On the other hand, a fuel economy standard is an intensity standard to regulate the consumption of fuel when considering fuel economy as gasoline consumption per mile travelled. Because vehicular consumption of fuel is highly correlated with pollutant emitted, fuel economy standards could be very effective in vehicular pollution control. Combining vehicle mileage tax with emission standards may achieve the first best solution. Similarly, combining fuel tax (or mileage tax) with fuel economy standards may also achieve the first best solution.

3.2 Emission Regulations

Compared to the manufacturing-origin or power plant-origin air pollution, the contribution of automobile (or mobile source) air pollution was realized relatively late because the vehicle’s emission was relatively small. In addition, in the 1920s and 1930s there were not many cars on the road accumulating pollutants up to a threshold that causes noticeable adverse health effects. This section provides an overview of the history of automobile emission regulations. A summary of key events is listed in *Appendix 1 Key Events of California and US Vehicle Emissions Regulation*.

3.2.1 California's Vehicle Emission Regulations

In the 1940s, Los Angeles was the first city publically concerned with the harmful health outcome of mobile source pollutants. Citizens of the Los Angeles basin suffered eye and throat irritation, reduced visibility and other health problems. In response to air pollution, Los Angeles began its air pollution control program and established the Bureau of Smoke Control in its health department. California became the first US state to set and enforce emission regulations when Governor Earl Warren signs into law the Air Pollution Control Act, authorizing the creation of an Air Pollution Control District in every county in the state on June 10, 1947.

In 1959, California enacted legislation requiring the state Department of Public Health to establish air quality standards and necessary controls for motor vehicle emissions. The first statewide air quality standards were set by the Department of Public Health for total suspended particulates, photochemical oxidants, sulfur dioxide, nitrogen dioxide, and carbon monoxide.

Amid the Federal Motor Vehicle Act of 1960 that required federal research to address air pollution from motor vehicles, California established the Motor Vehicle Pollution Control Board to test and certify devices for installation on cars for sale in California. Automobile tailpipe emission standards for hydrocarbon and CO were first adopted in the nation by the California Motor Vehicle Pollution Control Board in 1966.

The California Motor Vehicle Pollution Control Board, and the Bureau of Air Sanitation and its Laboratory merged into a new authority -- the California Air Resources Board (CARB) in 1967. CARB adopted the first automobile NO_x standards of the nation in 1971. CARB required elimination of the use of lead in gasoline and the addition of oxygenates in gasoline to cut carbon monoxide emissions by 10%.

Probably the most influential policy CARB imposed to the automobile industry is the setup of low emission vehicle (LEV) and zero emission vehicle (ZEV) standards beginning in 1990. The ZEV mandate was upheld in 2001, automakers were required to produce between 4,450 and 15,450 zero-emission cars starting in 2003. A new ZEV standard was adopted in 2008. From 2012, automakers must have at least 15% of their fleet vehicles be ZEVs in order to sell cars in California.

3.2.2 The US Nationwide Emission Control

The first nationwide emission standard came forth in 1970 when US Congress passed the Clean Air Act. The Act called for tailpipe emission standards to control pollutants including Carbon Monoxide (CO), Volatile Organic Compounds (VOCs), and Nitro Oxides (NO_x). The Act also set forth a dedicated agency to enforce the regulation of air pollution. This agency, the Environmental Protection Agency (EPA), was set up on Dec. 2nd 1970. The tailpipe emission standards came into effect in 1975, setting a NO_x standard for cars and light-duty trucks of 3.1 grams per mile (gpm).

In subsequent years, Congress kept amending the Act and tightening the standards (Tier 1 from 1990-1994, Tier 2 from 2004-2009). For example, the target allowable NO_x

emission was reduced to 1 gpm for cars in 1981, and 1.2 gpm for light duty trucks in 1988. The heavier trucks emission standard was first set at 1.7 gpm in 1988. The standard was further reduced to 0.6 gpm for cars and trucks, ranging from 0.6 to 1.52 gpm in 1994. The target NO_x emission standard set by the EPA in 1999 was to reach a fleet average of 0.07 gpm for all cars, smaller SUVs, Minivans, and Light Trucks in 2009.

In 1998, the Clinton Administration, as part of a voluntary agreement with auto manufacturers, created the National Light Emission Vehicle (NLEV) Program. The NLEV program combined federal and California motor vehicle standards and set emission reductions that were equivalent to the California Low Emission Vehicle (LEV) program. The program was phased-in through schedules that required car manufacturers to certify a percentage of their vehicle fleets to increasingly cleaner standards (LEV, and Ultra Low Emission Vehicle or ULEV). The NLEV program did not include the Heavy Light Duty Truck (HLDT, with Gross Vehicle Weight Rating or GVWR>6,000 lbs) vehicle category.

On March 16, 2004, the EPA Administrator signed a proposed regulation that instructs automotive manufacturers on how to conduct the durability procedures used to predict the useful life emissions of new vehicles. This rulemaking fulfills a court mandate issued on October 22, 2002, by the United States Court of Appeals for the District of Columbia Circuit Court that ordered the EPA to issue new emissions durability regulations

In 2014, the EPA finalized a new emission standards (Tier 3) that required vehicles to meet standards over the full useful life of 150,000 miles or 15 years (later reduced to an option of requirements over 120,000-mile / 10-year useful life), and targets the NO_x emission to 0.03 gpm for cars and trucks GVWR ≤6, 000lb by model year 2024.

3.2.3 Emission Controls in Europe and Other Countries

The European Union (EU) sets emission limits for most types of engines and vehicle[17], such as passenger cars and light duty commercial vehicles (up to 3.5 tons or approximately 7700 lbs), trucks and buses, motorcycles, engines for "non-road mobile machinery"[18], engines for agricultural and forestry tractors, and combustion heaters for motor vehicles and their trailers.

European Union emission regulations for new light duty vehicles (passenger cars and light commercial vehicles) were once specified in Directive 70/220/EEC with a number of amendments adopted through 2004. In 2007, this Directive was repealed and replaced by Regulation 715/2007 (Euro 5/6) [2899][19].

Currently, emissions of nitrogen oxides (NO_x), total hydrocarbon (HC), non-methane hydrocarbons (NMHC), carbon monoxide (CO) and particulate matter (PM) are regulated for most vehicle types, including cars, lorries, trains, tractors and similar machinery, and barges, but excluding seagoing ships and airplanes in the European Union. EU introduced emission standards gradually from Euro 1 (1992), Euro 2, to Euro

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[17] AECC: http://www.aecc.eu/en/Emissions_Legislation.html

[18] These include construction equipment (bulldozers, excavators, off-highway trucks etc.); road rollers and mobile cranes, fork-lift trucks, airport ground-support equipment, combine harvesters, snow-ploughs, railway locomotives and railcars and small equipment such as lawn mowers and chain saws

[19] The Euro 1 standards (also known as EC 93) are Directives 91/441/EEC (passenger cars only) or 93/59/EEC (passenger cars and light trucks), the Euro 2 standards (EC 96) are Directives 94/12/EC or 96/69/EC, the Euro 3/4 standards (2000/2005) are Directives 98/69/EC, further amended in 2002/80/EC, the Euro 5/6 standards (2009/2014) are Regulation 715/2007 ("political" legislation) [2899] and several comitology regulations.

6 stages (2014). EU regulations have different emission limits for *compression ignition* (diesel) and *positive ignition* (gasoline, natural gas or NG, liquefied petroleum gas or LPG, ethanol, etc.) vehicles. Diesels have more stringent CO standards but are allowed higher NOx. Positive ignition vehicles were exempted from PM standards through the Euro 4 stage. Euro 5/6 regulations introduce PM mass emission standards equal to those for diesels, and for positive ignition vehicles with DI engines.

Japan introduced vehicle emission standards in the late 1980's. However, the standards remained relaxed through 1990's. In December 2000, the Tokyo Metropolitan Government (TMG) adopted the "Countermeasure Against Vehicle Pollution" program. The program introduced regulations for diesel emission (named retrofit program), mandated the use of low emission vehicles, and introduced vehicle pollution inspectors. The Japanese vehicle emission control focuses mainly in NO_x and PM. In 2003, the Japanese Ministry of Environment (MOE) enforced very stringent emission standards for both light and heavy-duty vehicles while they are also subject to stringent fuel efficiency targets (described in section 3.3 in detail). By 2005, the Japanese heavy duty vehicle emission standards are the world's most stringent diesel engine emission standards with NO_x at 2 g/kWh (gram per kilo Walt hour[20]), and PM at 0.027g/kWh. The standards are further tightened in 2009 at the level between US2010 and Euro 6 standards.

Compared to the US, EU and Japan, China started vehicle emission regulation late (from 2000) because there were not many private automobiles on the road until 2000.

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[20] kWh, or kilo Watt hour is a unit of energy consumption, it is also used in measuring electricity consumption in US.

The Chinese vehicle emission control resembles the EU standard, focusing on controlling NO_x, CO, PMs and HCs. The Chinese standards Nation Standard I (NS I) though IV are equivalent to Euro 1 to Euro 6 Directives[21], respectively, with approximately 5 ~ 8 years' lag. Today, the main obstacles to achieving the emission control goal are the quality of motor fuels and the application of emission control technologies. The two major fuel suppliers of the country accounting for more than 90% of the fuel sale in China are state own enterprises. As of 2014, they are not able to produce low-Sulfur fuels. Thus, the emission of SO_x and related $PM_{2.5}$ from vehicles remain high. Meanwhile, the Chinese automobile industry adopted the new technologies for vehicle emission reduction very slowly due to market protection from international competition. Nevertheless, the Chinese vehicle emission standards elevated quicker. For example, the Euro 1 Directives started in 1992, and the Euro 5 started in 2008, taking 16 years. The Chinese NS I (Euro 1 equivalent) started in 2000, and the NS V started in 2013, taking 13 years.

Major economies such as the US, European Union, China, and Japan reached agreements to reduce CO_2 emission in adopting the Kyoto Protocol on Dec. 11, 1997. Since then, great efforts have been put into effect to control vehicle CO_2 emission in these countries. Though the US has not ratified the Kyoto Protocol, it also exerts tremendous effects to control CO_2 emission.

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[21] The Chinese government designs vehicle emission standards mainly based on EU standards

3.3 Fuel Economy Standards

Emission standards attempt to address the environmental problem associated with motor vehicles, and they do successfully make the vehicles “cleaner” – in the sense of less pollutants per unit (for example per mile a vehicle travels). They do help much in reducing the total amount of pollutants. However, the effect of reduction of per unit emission is compromised if vehicles consume more fuel (eg. equipped with more emission control units that increases the weight of the vehicle[22]), or people drive vehicles more since the externality is positively correlated to the amount miles travelled, *ceteris paribus*. Thus, policies controlling the consumption of fuel are another crucial aspect in reducing the mobile source air pollution. This section provides an overview of the history of fuel economy standards.

In the United States, the EPA sets emission standards (greenhouse gas (GHG), exhaust, and evaporative as well as gasoline sulfur standards, etc.) under the Clean Air Act, while the National Highway Traffic Safety Administration (NHTSA) sets vehicle fuel economy standards - Corporate Average Fuel Economy (CAFE) standards - under the Energy Policy and Conservation Act.

3.3.1 Corporate Average Fuel Economy (CAFE) Standards

Introduced in 1970s and put into effect in 1975 in the US, the Corporate Average Fuel Economy (CAFE) standards are the main tools regulators used to regulate the

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[22] Generally, the heavier the vehicle, the more power needed to propel, hence the higher consumption of fuel.

automobile industry to design and produce more fuel-efficient vehicles in order to lower the consumption of oil and reduce air pollution (Sallee 2010, Soren Anderson, Ian Parry et al. 2010). The principal is to reduce overall oil consumption by reducing the fuel-consumption rates of vehicles (i.e. improving the fuel economy of vehicles). CAFE standards consist of a set of milestone fuel economy standards for passenger cars and light duty trucks. CAFE standards require an automaker's car fleet to meet a sales-weighted average of 18 miles per gallon (mpg) in the 1970s, which increased steadily to 27.5 mpg by 1985. A lower standard was established for light trucks (pickups, minivans, and sport utility vehicles or SUVs), which rose from 16 mpg in 1980 to 22.5 mpg in 2008. The standard has tightened under the Obama administration. Hall (2011) has an excellent review on the evolution of CAFE standards. Today, CAFE standards also play an important role in reducing fuel consumption and pollutant emission (Hall 2011).

The evolution of CAFE can be divided into three stages: Rapid improvement from 1980 until 1987, and two stagnant decades until 2009, and raising to a higher standard from 2009.

In 1973, Arabic members of the Organization of the Petroleum Exporting Countries (OPEC) proclaimed an oil embargo (term Oil Embargo) against Canada, Japan, the Netherlands, the United Kingdom and the US. The Oil Embargo drastically drove up the price of oil, and reduced the world oil supply, creating the “Oil Crisis” in the 1970s. Being the largest oil consumer, the US was hit the most by the Oil Embargo.

In response to the Oil Embargo, the US Congress passed the Energy Policy and Conservation Act (EPCA) in 1975. The Act authorized the rationing of energy supplies, directed the creation of strategic petroleum reserves, and mandated energy conservation programs at the state and federal levels. In addition, EPCA mandates motor vehicle fuel economy regulations. One of them is the Corporate Average Fuel Economy (CAFE) standards. The CAFE standards require that all manufacturer's passenger car and light truck fleets meet a prescribed fuel economy measured by miles per gallon (mpg) rating for each model year, or otherwise pay a penalty, per car sold, equal to $5 multiplied by each tenth of an mpg fallen short of the standard. EPCA defines a manufacturer's fleet-wide fuel economy as the average fuel economy rating of all vehicles it sold in a given model year.

EPCA authorizes the Secretary of Transportation to amend CAFE standards through the rulemaking process to a level determined to be the maximum feasible average fuel economy for a given model year, subjected to congressional approval if the proposed car standard was outside the prescribed range. The National Highway Transportation and Safety Administration (NHTSA) sets forth the standard under the authority of the Secretary of Transportation.

EPCA established the initial standard of 18 mpg for car fleets in model year 1978, representing a 29% improvement from the pre-regulation average fuel economy of 13.9 mpg. The final proposed standard was to achieve the fuel economy of 27.5 mpg for model year 1985 and thereafter. With a narrow range between 26 and 27.5 mpg after 1985. The Act initially did not require setting the standard for light duty trucks, leaving this to the Secretary of Transportation.

The CAFE standards continued to increase until the Reagan Administration. However, in the mid-1980s amid the decline of price of oil and severe competition from Japanese automakers who provided more fuel efficient vehicles, Ford and GM lobbied the Reagan Administration to lower the standards. As a result, NHTSA lowered the standard for the first time from 27.5 mpg to 26 mpg, below the benchmark set by Congress in 1986, the minimum allowable without congressional approval. At the industry's urging, for the subsequent three years NHTSA had not changed the fuel economy standard levels. NHTSA also did not raise light truck standards during this period, holding them at 20.5 mpg. NHTSA restored the 27.5 passenger car standard, but lowered light truck requirements to 20 mpg in 1989.

The CAFE standards were not increased during the Bush and Clinton Administrations in the 1990s. Though the Clinton Administration had tried to raise them, efforts were undermined by Congress who took away the Administration's authority to increase fuel efficiency standard. In 1990, Senators Richard Bryan and Slade Gordon sponsored legislation raising fuel economy standards for cars and light trucks by 40% over the next ten years. However, the bill was not passed by Senate. In April 1994, NHTSA announced it would raise light-truck CAFE standards by 40% over the next ten years (1998-2006) from then current level (20.5 mpg) to as high as between 26 and 28 mpg. However, Congress responded with legislation not to impose CAFE standard increases during 1996, 1997 and 1998. The Permanent CAFE "freeze" bills was introduced in the House (H.R. 880) and the Senate (S. 286) in February 1997, and was re-introduced in 1999. President Clinton signed the DOT budget for FY2000, extending the

CAFE freeze for another year on October 9th, 1999. Both the House and the Senate agreed to continue the CAFE freeze for another year in May and June 2000, respectively.

The CAFE standards were finally increased under the Energy Independence and Security Act (EISA) during the Bush (Jr) Administration in 2007, requiring that the combined car and light truck fleet fuel economy reach 35 mpg by 2020, and raising light duty truck standards from 22.2 mpg to 24 mpg between model years 2008 and 2011. In 2009, President Obama announced plans to address climate change by tightening motor vehicle fuel economy standards. On July 29th, 2011, President Obama announced the proposed standards, agreed upon by thirteen large automakers, to increase fuel economy to 54.5 mpg for cars and light duty trucks by model year 2025. This was finalized in the new CAFE standard on Aug. 28th, 2012.

3.3.2 European Fuel Economy Standards

In the European Union, vehicle fuel economy is measured at the level of carbon (CO_2) emission per unit distance travel – gram of CO_2 per kilometer travel or gCO_2/km[23].

The European automotive manufacturers are committed to reducing passenger vehicle CO_2 emissions through a voluntary agreement with the European Commission signed in March 1998, named the ACEA Agreement. It is a collective action by automobile manufacturers and their association, Association des Constructeurs Européens d'Automobiles (ACEA), to voluntarily reduce the CO_2 emission rates of vehicles sold in the European Union. The agreement establishes industry-wide targets for

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[23] The conversion between MPG and gCO_2/km is MPG ~ 5457 / gCO_2/km for gasoline vehicles, ~ 6233 / gCO_2/km for diesel vehicles.

average vehicle emissions of new vehicles sold in Europe, reducing to 140 $g\text{CO}_2$/km (~ 39 mpg[24]) by 2008, and to 120 $g\text{CO}_2$/km (~ 45.5 mpg) by 2012. Comparably, in 2002, the average CO_2 emissions from ACEA's new vehicle fleet was 165 *g*CO2/km (~33 mpg).

3.3.3 Fuel Economy Standards in Other Countries

Japan started fuel economy regulation in 1979, applicable to new gasoline cars from 1985. In 1999, the Japanese government established a set of fuel economy standards for gasoline and diesel powered light-duty passenger and commercial vehicles to meet fuel economy targets by 2010. The standards are weight class based standards where lighter vehicles have higher fuel economy requirements. Today, Japan has the world’s most stringent fuel economy standards. Vehicles weighing 1550 to 1824 lb (models similar to the Ford Fiesta, Toyota Yaris, and Honda Fit in the US market) must meet a fuel economy equivalent to 44 mpg in 2010. It is 42 mpg for vehicles weighing from 1826 to 2238 (models similar to the Ford Focus, Toyota Corolla, and Honda Civic in the US market), and 37.5 mpg for vehicles weighing from 2240 to 2789 (models similar to the Ford Fusion, Toyota Camry, and Honda Accord in the US market). In 2005, Japanese automobile manufacturers were all able to meet the 2010 target standards. In 2007, Japan adopted 2015 fuel efficient targets for light vehicles. The 2015 fuel efficient regulation introduced more vehicle weight categories, and mandated a 23.5%, 12.5%, and 7.2% increase over 2010 standards in passenger cars, light trucks and small buses, respectively.

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[24] Conversions are done by using the calculator provided by Unit Juggler (https://www.unitjuggler.com/convert-fuelconsumption-from-gperkmgasoline-to-mpg.html)

China also introduced regulations for fuel economy standards for new vehicle fleets. The regulations set two phases: Phase 1 took effect on July 1st, 2005 for new vehicle models, and on July 1st, 2006 for continued vehicle models. Phase 2 took effect on January 1st, 2008 for new models and on January 1, 2009 for continued vehicle models. The standards are classified into 16 weight classes, ranging from vehicles weighing less than 750 kg (approximately 1,500 lbs) to vehicles weighing more than 2,500 kg (approximately 5,500 lbs). The target requirements are standards of approximately 40 mpg, 38 mpg, and 30 mpg corresponding to the above Japanese weight categories.

Other countries or region such as Australia, Canada, South Korea and Taiwan also have regulations on vehicle fuel economy.

3.4 Fuel Component Control

Fuel component control is to regulate the level of certain chemical elements in the fuel. The two most regulated elements are lead and sulfur.

Although crude oil contains many metal elements, which may eventually get into motor fuel after refinery, lead is not a significant natural component of it. Rather, lead was added into the gasoline during the refinery process in a chemical named “tetraethyl lead” since the 1920’s to help reduce engine knocking, boost octane ratings, and reduce wear and tear on valve seats within the motor. However, lead is a poisonous heavy metal. Any absorption of lead into the body has detrimental effects, particularly on the early development of nervous systems in children and fetuses. In the US, after environmental hazards became overwhelmingly apparent, the EPA announced a scheduled phase out of lead content in gasoline in 1974. Selling leaded gasoline to automobiles became illegal in 1986. On January 1st, 1996, the Clean Air Act completely banned the use of leaded fuel for any on road vehicle. Many countries stablished programs to completely phase-out the use of leaded gasoline. Unleaded gasoline has been required throughout the European Union since 1989 and is widely available in Poland, Hungary and the Czech Republic. To the year 1996, most western countries banned the sale of leaded gasoline. In 1999, unleaded gasoline accounted for 80% of total sales worldwide. The European Union banned leaded gasoline sale in 2000. China also banned leaded gasoline sale in 2000. Today, lead only exists in automobile fuel in trace amount due to its natural existence in crude oil.

Sulfur in gasoline or diesel is undesirable. Not only is it the source of pollutants SO_x, but also can cause defects in the vehicle's catalytic converter, a component to reduce the emissions of CO, NO_x and HCs, reducing its efficiency. The state of California has regulated sulfur in gasoline since the 1990s to a level of 30 ~40 ppm, about one tenth of the level in many other states. The EPA recommended a level between 150 and 250 ppm in 1997. In 1998, the state of Georgia became the second state to regulate the sulfur content of gasoline at a sulfur limit of 150 ppm. The EPA promulgated the rules on gasoline sulfur control on Feb. 10th, 2000 to cap the sulfur level at 120 ppm in 2004, requiring a reduction to an 80 ppm cap and a 30 ppm average by 2006, and 10 ppm at the beginning of year 2017. The EPA issued a final rule that required diesel fuel contain no more than 0.05% by weight (~ 500 ppm) by October 1993 on May 7th, 1992. This helped reduce particulate matter emission from heavy duty vehicles by 90%. Since then, sulfur levels in diesel have been significantly reduced by the refineries of the oil industry. The Atlantic Richfield Company announced to sell ultra-low sulfur diesel at a level of 15 ppm on Dec. 15th, 1999. The EPA proposed a rule that would cap the sulfur level in highway used diesel at 15 ppm beginning in the year 2010 on Jun. 2nd 2000. Canada and many other countries have similar requirements of diesel fuel sulfur levels today.

3.5 Vehicle Usage Regulations

Many countries adopt different policies to regulate the usage of vehicle in order to reduce aggregate vehicle driving. The prevailing policies are toll roads, congestion charge zoning, vehicle ownership control, selective driving permission, and Electronic Road Pricing (EPR) systems, etc. They are discussed in the following paragraphs accordingly. These policies increase the costs of either vehicle ownership or operation.

Toll roads are roads with direct charges levied for use. Tolls can be set in congested areas to discourage driving. Toll roads can create disincentive for driving by increasing the cost of using the road, thus reducing pollution. However, in most countries, toll roads, toll bridges and toll tunnels are used primarily for revenue generation to repay long-term debt issued to finance the toll facility, or to finance capacity expansion, operations and maintenance of the facility itself, or simply as general tax funds.

Introduced on 17 February 2003, the city of London imposed a Congestion Charge for driving a vehicle within the charging zone between 07:00 and 18:00, Monday to Friday. From 2014, drivers need to pay an £11.50 daily charge per car driving (initially, the fee was £5) within the zone with a penalty between £65 and £195 levied for non-payment. Low-emission vehicles are exempt. Congestion Charge Zoning covers the area within the London Inner Ring Road (including both the City of London and the West End) with approximately 136,000 residents.

The Swedish capital Stockholm imposed a congestion tax levied on most vehicles entering and exiting central Stockholm starting on August 1st, 2007.

Since 2014, many Chinese cities have limited new car purchasing by putting restrictions in license plate issuing. In cities such as Beijing and Tianjing, applications for vehicle license plates are put into a lottery. Buyers (applicants) have a certain chance (~55%) to win non-transferable license plates to use in new vehicles. Buyers can reapply to the next lottery draw after a probation period (varied based on demand) if they did not get the license in the previous draw. In other cities such as Guangzhou, a certain number of new vehicle license plates are auctioned in public for immediate issuance. Otherwise, buyers have to wait for a long waiting period (eg. 1 year or more) for the issuance. Thus, buyers effectively pay penalties (auction price) to own non-transferable license plates immediately. The revenue of the auction is set into a highway maintenance fund.

On Nov. 3rd, 2014, Beijing, the capital of China, enacted a rule that restricts vehicle driving based on vehicle license plate - vehicles with certain numbers in their license plates can only be driven in the city area in certain days of the month (or weeks). Since then, metropolitans in China such as Shanghai, Tianjin and Guangzhou have also proposed timelines to adopt such policy. The Mexico City of Mexico also has similar policy. The policy, named *Hoy No Circula*, was taken into effect in 1989. It bans most drivers from using their vehicles one weekday per week between 5 a.m. and 10 p.m., based on the last digit of the vehicle's license plate and affect the vast majority of residential and commercial vehicles but excluding Taxis.

Singapore implemented Electronic Road Pricing System (ERP) in regulating the vehicle flow within the city area during certain times of day in 1998. The ERP in Singapore is a usage-based taxation mechanism to complement the purchase-based Certificate of Entitlement system. The ERP system consists of ERP gantries located at all roads linking into Singapore's central business district as well as the expressways and arterial roads with heavy traffic. The gantry system is a system of sensors on two gantries, one in front of the other. Cameras are set in the gantries to capture the rear license plates of vehicles. A device named In-vehicle Unit (IU) is affixed on the lower right corner of the vehicle’s front windscreen, in which a stored-value card, the Cash Card (or EZ-Link), is inserted for the payments of the road usage charges. The second generation IU accepts the Cards. The cost of an IU is 150 Singapore dollars. It is mandatory for all Singapore-registered vehicles. Foreign vehicles must rent an IU to be lawful in riding on Singapore roads. When a vehicle equipped with an IU passes through an ERP gantry, a road usage charge is taken from the Cash Card in the IU. The charge for passing through a gantry depends on the location and time, with the peak hour being the most expensive. For example, passing 5 gantries in peak time costs a total of 15 Singapore dollars. A vehicle owner will receive a fine, a bill for the short of ERP charge, and a 10 dollars administration fee by mail if he/she does not have sufficient funds in their CashCard (or EZ-Link) when passing through an ERP gantry. Hong Kong started using ERP in 1983-1985 as a pilot test to regulate traffic flows. However, it had not moved forward since then due to public opposition. The city of Toronto, Ontario, Canada has similar ERP system used in Highway 407.

3.6 Other Regulations or Economic Instruments

The Global Fuel Economy Initiative (GFEI) of the United Nations Environment Programme evaluates the regulations and/or economic instruments on vehicles in different countries or regions. According to their studies, the other instruments adopted by various countries[25] are fee-bates, fuel taxation, penalties, buy-backs, priority lanes, free or subsidized parking, etc.

Fee-bates are fees on vehicles with inefficient technology and rebates to the efficient vehicles. They are fiscal policies to encourage car buyers to choose higher fuel efficient and/or lower emission vehicles cars, and to encourage manufacturers to design and produce them. Currently France, Chile, Austria, Belgium, Denmark, and Singapore have this policy.

Fuel taxation can be a very important tool for internalizing the external costs of automobiles - road infrastructure maintenance, adverse health effects due to transport-related pollution, and climate change, as well as encouraging the desired economic behaviors. Almost all countries have some kind of fuel taxes in place. By far, fuel tax is the instrument with the least marginal cost to implement: collecting at the point of sale. However, it is not favored in many countries due to legal and political restraints. In the United States, fuel tax is mainly for the purpose of collecting funds to support highway

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[25] Source: http://www.unep.org/transport/gfei/autotool/instruments.asp

facilities and road maintenance rather than a policy instrument to regulate driving behaviors.

Penalties are fees imposed upon vehicle manufacturers for failure to meet certain standards: emissions, fuel economy, or consumption standards. US, China, Japan, and most European countries have penalties for new vehicles fail to meet these standards. In the US, from 1983 to 2004, manufacturers had paid more than $618 million in civil penalties for failing to meet CAFE or emission standards. In the European Union, a manufacturer must pay an excess emission premium per car (€5 for the first g/km of excess, €15 for the second g/km, €25 for the third g/km, and €95 for each subsequent g/km) if the average CO_2 emissions of a manufacturer's vehicle fleet exceed a limit in any year from 2012 forward. The first g/km of excess will cost a €95 premium from 2019 forward. China places a tax structure that penalizes large-engine cars and encourages the purchases of more fuel-efficient cars. For example, effective Sept 1st 2008, a 1.5 -2.0L engine car will be assessed a marginal tax rate of 5%. Comparably, the tax rate is 3% for a 1.0-1.5L engine car.

Buy-backs provide monetary or other incentives to vehicle owners to voluntarily give up their older, often more polluted vehicles. Payments or incentives may be awarded directly to the buyers or vendors of the new vehicles, or by the form of tax benefits. For example, in August 2009, the US federal government provided one time rebates, $3316 or $3868 depends on certain criteria, to prospective car buyers toward the purchases of new, fuel-efficient vehicles, if the trade-in vehicles were scrapped. This Car Allowance

Rebate System (CARS), or colloquially known as the “Cash for Clunkers” program, costs the US federal government about $3 billion.

Priority lanes are dedicated road lanes for vehicles meet certain criteria. For example, the High Occupants Vehicle (HOV, vehicles with more than 2 occupants) lanes, or carpool lanes in many US metropolitan areas. Carpooling reduces the number of vehicles on road hence reduce the number of sources of pollution. In California, cars meeting certain emission standards can use HOV lanes without the restriction on the number of occupants. Although priority lanes create incentives to carpool or purchase the low emission vehicles, it encourages driving because the cost of driving in priority lanes is reduced in terms of cost splitting and time saving. Thus, the effects of priority lanes in reducing driving externality is ambiguous.

CHAPTER IV

LITERATURE REVIEW

The literature spans greatly on the effects of automobile emission standards and fuel economy standards, and on the health outcomes related to air pollution. I intend to cover a few keynotes of them. The chapter is organized as the following. Section 4.1 summarizes the literature on the effect of emission standards. Section 4.2 summarizes those on the effects of fuel economy standards. Section 4.3 summarizes those on the health outcomes that related to air pollution. My findings and contribution to effects emission standards on mobile source air pollutants, and fuel economy standards on vehicle fuel economy are described at the end of section 4.1 and 4.2, respectively.

4.1 Emission Standards

I inspect at the emission standards first because they are policies directly regulating the air pollutants that are related to health. Though different countries have different emission standards (Faiz, Weaver et al. 1996, Kodjak 2015), the main goal is to reduce the per unit (fuel consumption or miles travel) level of pollutants. The most significant effects of emission standards are divided into two categories. First, the enactment of (increasingly stringent) automobile emission standards reduce the vehicle pollutants emitted, hence significantly improving the air quality. Second, the automobile emission standards force the automobile industry to develop and adopt technologies to reduce emissions, hence advancing the technology. The effects of emission standards on reducing the mobile source pollutants are significant. For example, Chambliss et al. (2013) project that emission and fuel standards in the EU, the United States, Canada, Japan, Australia, and South Korea will reduce transportation-related emissions and health impacts in 2030 to levels 85 percent below year-2000 levels, even with a 50 percent increase in vehicle activity in their analytic framework. However, this is not true in other countries of the world, especially in fast developing countries in Africa, Middle East and Asia. For these countries, the projected growth in vehicle activity and urbanization will undermine the positive effects from their current emission standards. Their failure to catch up with developed countries will compromise the efforts that have been made by developed countries. Thus Chambliss et al. call for a universal standard of the cleanest vehicles and fuels (Chambliss, Miller et al. 2013).

Saikawa et al. (2011) study the impact of the adoption of Euro 3 emission standards in reducing vehicle emissions of carbon monoxide, nitrogen oxides, non-methane volatile organic compounds, black carbon, and organic carbon in China. They estimate that if all on-road vehicles meet the Euro 3 regulations in 2020, these emissions would be reduced by more than 50% relative to 2000. Meanwhile, the implementation of stringent vehicle emission standards leads to a large, simultaneous reduction of the surface ozone (O_3) mixing ratios and particulate matter ($PM_{2.5}$) concentrations. Kodjak et al. (2015) estimate that the European emission standards would eventually reduce $PM_{2.5}$ by 99% compared to no emission control in G20 nations. [26]

Emission standards promote advances in technology. Under the pressure of regulation, automobile manufacturers must seek new technologies to reduce tailpipe emissions. The vehicle emissions-control hardware has improved greatly over the past 50 years since the introduction of emission regulation. The efforts of motor vehicle manufacturers, the manufacturers of emissions controls and other equipment, and the regulatory authorities have made vehicles much cleaner and more durable (Council 2006). These improvements in vehicle emission control in turn attract purchases. Interestingly, the technological innovation required by the emission standards also resulted in greater fuel efficiency and better combustion, so that improved the fuel economy (Espey 1997). The emission standards also confer a competition advantage for automobile manufactures. Initially, automobile manufactures argued that tight emission standards would create comparative market disadvantage due to increased cost to develop and implement the technology to control emissions. However, it turned out to be the opposite. For example, the US auto industry argued that strict standards in the US reduced its ability to compete in the international marketplace due to the costs of achieving compliance when the Clean Air Act was passed in 1970.

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[26] G-20 is a group of finance ministers and central bank governors of 19 countries and the European Union. The 19 countries are Australia, Brazil, Canada, China, Argentina, France, Germany, India, Indonesia, Italy, Japan, Mexico, Russia, Saudi Arabia, South Africa, Republic of Korea, Turkey, United Kingdom, and United States of America.

In April 1973, the US postponed implementation of the 1975 nitrogen oxide emission standard until 1976. Eventually, the proposed 1978 nitrogen oxide emission standard was not met by the US auto industry. On the contrary, the Japanese auto industry took active effects to meet the US emission standard in order to promote sales in US market. By 1978, all Japanese automobile manufacturers meet the US nitrogen oxide emission standard of 1978. The Japanese industry was not disadvantaged by applying stringent environmental regulations. In fact, the technological innovation required by the emission standards also resulted in greater fuel efficiency and better combustion, giving Japanese companies a competitive advantage, particularly against less fuel efficient American cars. During the 1980s, the Japanese automobile companies gained increased market share in automobile sales. Contrary to the thought that compliance to stringent emission standards would increase the cost in production and create competitive disadvantage, Porter (Porter and Linde 1995) argued that strict environmental regulations would induce efficiency and encourage innovations that help improve commercial competitiveness[27].

In my analysis on the mobile source criteria pollutants[28] (CO, NO_x, and $PM_{2.5}$) data collected by US EPA, clearly decreased trends of average pollutant levels (measured by their corresponding concentration units) on every states from 1995 to 2012 are

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[27] Unlike the fuel economy standards, the emission standards do not create the rebound effect as described in section 4.2.

[28] The US EPA terms the six pollutants commonly found in the US as criteria pollutants. They are particulate matters, photochemical oxidants and ground-level ozone, carbon monoxide, sulfur oxides, nitrogen oxides, and lead.

observed (see Chapter VII). This provides an empirical evidence of the effects of automobile emission standards in improving air quality.

4.2 Fuel Economy Standards

Similar to the emission standards, the effects of fuel economy standards reduce the fuel consumption and air pollutants, and promote the automobile industry develop and adopt fuel efficiency technologies. In addition, fuel economy standards create consumer incentives in purchasing the fuel-efficient vehicle in order to reduce fuel cost. However, fuel economy standards also create negative impacts, such as the undesired rebound effects.

The primary purpose of enforcing fuel economy standards such as CAFE is to reduce the per unit fuel consumption of vehicles, ideally to a minimum that can operate the vehicle to meet the designed function. The fuel economy standards have strong reductions in fuel consumption and emissions of greenhouse gases, impacts on safety, and impacts on technology adoption in the automobile industry (Council 2002). Greene studies the effects of CAFE and finds CAFE standards had a significant effect in reducing the fuel consumption from 1977 to 1989. He attributes an approximately 75% of the reduction attributed to CAFE standards other than gasoline price changes (Greene 1990). Meanwhile, the emitted pollutants from automobiles will decrease when the fuel consumption reduces, *ceteris paribus*. Thus, fuel economy standards also contribute to the emission reduction. DeCicco projects, after accounting by oil price fluctuation, the fuel saving and emission reduction could be as large as 2.9 million barrels and 147 million metric tons, respectively, per year by 2010 in US attributed to CAFE standards (DeCicco 1995).

However, improving fuel economy reduces drivers' fuel costs per distance driven. It encourages drivers to travel more and thus consume more fuel (Blair, Kaserman et al. 1984). This is the rebound effect (RE) and it is extensively studied (Greene 1992, Greene, Kahn et al. 1999, Buluş and Topalli 2011). Rebound effect compromises the overall effectiveness of fuel economy standards. Borenstein (2013) estimates that rebound effect compromises at least 10~30% of the effect of targeting reduction of oil consumption though the magnitude of rebound effects are still controversial among researchers. Besides, more driving increases the other externalities such as those described in section 2.3. Another problem, particularly in the US, associated with fuel economy is the decrease of the tax revenue from fuel sales that are necessary to fund highway infrastructure (Starr McMullen, Zhang et al. 2010). Because cars are more fuel-efficient over time, they consume fewer fuels so that less fuel tax is collected. In fact, US Highway Trust Fund suffers a large deficit due to the recent economic downturn and more fuel-efficient cars on road. Because of the existence of rebound effects, whether improving fuel economy of vehicle fleet will result in less fuel consumption and less air pollution is unclear. Harrington links EPA fuel economy certification data to a database of motor vehicle emissions. He finds that better fuel economy is strongly associated with lower emissions of CO and HC and that the effect gets stronger as vehicles age (Harrington 1997). In his quantitative model using the same data from Harrington, Espey finds that air pollutants reduction with respect to fuel economy depends on how tailpipe emissions are regulated and how consumers respond to the benefit of fuel economy (Espey 1996, Espey 1997). If the United States were to regulate tailpipe emissions per gallon of gasoline burned, increasing fuel efficiency would help to reduce overall pollution. However, Fischer et al. (2007) are not able to find significant reductions in automobile emissions to fuel economy improvement. Nevertheless, Hall (2011) argues that in a long run, CAFE standard will reduce the CO_2 emission and suggests an elevated CAFE standard over time.

Fuel economy standards also create an incentive for consumers in purchasing fuel-efficient vehicles. The better fuel-efficient means more savings in fuel cost. Rational consumers are more willing to buy better fuel-efficient vehicles so long as the lifetime savings from fuel efficiency are greater than the marginal cost. This in turn will promote automobile manufacturers to produce better fuel-efficient vehicles. This effect is stronger when fuel price is higher (Busse, Knittel et al. 2009). Dahl and others estimate the long run elasticity of the automobile fuel economy with respect to fuel prices to be about 0.5 (Dahl and Sterner 1991). Burke also finds that higher gasoline prices induce consumers to substitute to vehicles that are more fuel-efficient (Burke and Nishitateno 2013). However, using a non-linear maximum likelihood model on an international dataset, Espey finds that consumers' choice of vehicle fuel efficiency is less sensitive than Dahl estimated. To evaluate the effect of fuel economy standards on consumer choice, it is important to understand how consumers value the vehicle fuel economy and whether they can correctly expect the savings and rationalize their choices. Helfand and Wolverton (2009) provide an excellent review of the research on consumers' and automobile manufacturers' behaviors. They describe three kinds of evidence of consumer valuation on fuel economy (undervaluation, about-right valuation, and overvaluation). They raise the question of whether automakers build into their vehicles as much fuel economy as consumers are willing to purchase. They examine possible reasons for why there may be a gap between the amount consumers are willing to pay for fuel economy and the amount that automakers provide however do not find evidence to support any hypothesis. Meanwhile, the US EPA evaluates 28 econometric studies on consumer valuation on vehicle fuel economy. The estimates of consumers' willingness to pay for fuel economy improvements vary greatly hence no clear conclusion can be drawn on how consumers' value future fuel savings in making car buying decisions (EPA 2010)[29].

Fuel economy standards also encourage manufacturer to seek for alternative technologies. Michalek et al. (2005) evaluate the impact of fuel efficiency and emission policies on the long-term decision of vehicle design in a mathematical framework incorporating engineering design, cost of production, demands, market competition and game theory. They show that the CAFE standard results in increased fuel efficiency at a lower manufacturing cost. Meanwhile, regulation (penalty) provides incentive to design smaller, cheaper engines. They argue that a stricter standard is a better approach to achieve the fuel economy goal. However, under a variety of panel regression specifications using fleet and firm-level regulatory compliance data, MacKenzie (2012)

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[29] Behavioral economists provide an alternative theory: consumers will discount them heavily relative to certain initial costs because future fuel savings are inherently uncertain.

finds CAFE standards have no significant effects on rate of technology improvement when fleets were more tightly constrained by a CAFE standard.

To my knowledge, there is no literature in empirical research so far that evaluates the relationship between fuel economy standards and health outcomes. Specifically, there is no study that analytically elucidates the mechanism of reduction of air pollution through which fuel economy standards improve health. This makes my dissertation a unique contribution to the research community.

In my analysis, a steady increase in vehicle fuel economy, measured by miles per gallon, over time is observe on the vehicle data from the US Department of Transportation (US DOT). In the dissertation, I seek to attributes health outcomes to the vehicle fuel economy through the mechanism of air quality.

4.3 Health Outcomes Related to Polluted Air

In section 2.2, I summarized the detrimental health effects and the costs of pollutants from automobile emissions from various sources. Physicians, scientists, politicians and the public have recognized the impacts of automobile air pollution on the public heath for decades. There is a large body of research - in medical, science, and public policy fields - on the adverse health effects of air pollution, and air pollution attributed to automobiles[30]. Brunekreef and Holgate (2009) provide an excellent review

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[30] Watson et al. and Holgate et al. compiled details of this research in the books *Air Pollution, The Automobile and Public Health* published in 1989, and *Health Effects of Air Pollution* published in 1999, respectively.

on the evidence for adverse effects on health of selected air pollutants (ozone, particulates, nitrogen dioxide).

Pope et al. (1995), using ambient air pollution data from 151 U.S. metropolitan areas, explore the relationships of air pollution to all-causes. Lung cancer, and cardiopulmonary mortality was examined using multivariate analysis which controlled for smoking, education, and other risk factors. They find that particulate air pollution was associated with cardiopulmonary and lung cancer mortality but not with mortality due to other causes. Their work is a very important contribution to our understanding of airpollution and health, and is widely cited in the research field.

Increased mortality is associated with sulfate and fine particulate air pollution at levels commonly found in U.S. cities. Brunekreef et al. (1997) measured lung function in children living near motorways in the Netherlands. They find that the children's lung function was associated with truck traffic density but had a lesser association with automobile traffic density. The association is stronger in children living closest (<300 m) to the motorways and is stronger in girls than boys. Their results suggest that exposure to traffic-related air pollution may lead to reduced children's lung function. Künzli et al. (2000) estimate the impact of outdoor and traffic-related air pollution on public health in Austria, France, and Switzerland. They find traffic-related air pollution caused 6% of total mortality or more than 40 000 attributable cases per year. About half of all mortality caused by air pollution was attributed to motorized traffic, accounting also for: more than 25 000 new cases of chronic bronchitis (adults); more than 290,000 episodes of bronchitis (children); more than half million asthma attacks; and more than 16 million person days of restricted activities.

Brunekreef et al. (2009) and Beelen et al. (2008) study the effects of long-term exposure to traffic-related air pollution on respiratory and cardiovascular mortality in the Netherlands. In 2002, they report clear indications that traffic-related air pollution was related to cardiopulmonary mortality in a randomly selected sub-cohort of 5,000 older adults participating in the ongoing Netherlands Cohort Study (NLCS). The mortality risks associated with both background air pollution and traffic exposure variables were much smaller in a subsequent report using more refine estimation frameworks.

Chen et al. (2008) conducted a systematic review of all studies published between 1950 and 2007 of associations between long-term exposure to ambient air pollution and the risks in adults of non-accidental mortality and the incidence and mortality from cancer and cardiovascular and respiratory diseases. They find that long-term exposure to $PM_{2.5}$ increases the risk of non-accidental mortality by a 6% margin (per a 10 ug/m^3). Exposure to $PM_{2.5}$ was also associated with an increased risk of mortality from lung cancer (range: 15% to 21% margin) and total cardiovascular mortality (range: 12% to 14% margin). Living close to busy traffic appears to be associated with elevated risks of these three outcomes.

The negative impacts of air pollution on health are many. Thus, human beings will enjoy better health outcomes if all air pollutants are reduced.

CHAPTER V

HYPOTHESIS, EMPIRICAL STRATEGY AND ESTIMATION FRAMEWORK

I study the health effects of vehicle fuel economy standards, and seek to establish the mechanism through the air quality improvement. I am focusing on the relationship between vehicle fuel economy and asthma through the changes of air pollutants. The air pollutants of concern are mobile source pollutants such as carbon monoxide (CO), Nitrogen Dioxide (NO_2), and very fine Particulate Matter ($PM_{2.5}$).

This chapter describes the motivation, research hypothesis, and the empirical estimation strategy using statistical mediation analysis method. The chapter is organized as followed: section 5.1 describes the motivation of the research and the hypothesis; section 5.2 introduces the method in the empirical analysis – the statistical mediation analysis; section 5.3 delineates the empirical estimation models under the statistical mediation analysis framework.

5.1 Motivation and Hypothesis

In principle, CAFE standards would improve the average fuel economy of automobiles in the long run because more and more new fuel efficient automobiles are put on the road, and old fuel inefficient automobiles are scrapped. The overall improvements in fuel economy of the vehicle fleet would reduce the overall amount of fuel consumption[31], hence, reducing the emission of air pollutant.[32] Because air quality (the level of pollutants) correlates with respiratory disease asthma,[33] the incidence and/or prevalence of asthma will decrease if air quality is improving. Thus, a better health outcome is attributed to the improvement of vehicle fuel economy. This idea is also consistent to the Regulatory Impact Analysis (RIA) for CAFE standards from the US EPA and NHTSA.[34]

My hypothesis is that better vehicle fuel economy improves health, in particular asthma, through the reduction of mobile source pollutants. This implies a causal relationship between vehicle fuel economy and asthma transmitted by the mechanism of the change of mobile source air pollutants. This causal relationship is justified (in environmental and health science) outside of econometric analysis[35] so that a specification of causal relationship in econometric analysis is not necessarily formulated.

I seek empirical evidence to support this hypothesis through analyses on the available data of vehicles, air pollutants, and health surveys on asthma. The empirical estimations are based on the variations of fuel economy, air pollutants, and asthma occurrences over time. I estimate the effect of fuel economy on asthma, through the variations of the mobile source air pollutants (e.g. CO, NO_2, and $PM_{2.5}$). Note that in the

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[31] Although people may drive more due to the saving from fuel efficiency (rebound effects), they are also constrained to the time that they can allocate for driving. Thus, most people may not “rebound” enough to exhaust the fuel saving.

[32] Assume there is a positive correlation between fuel consumption and emitted pollutants. This can be justified scientifically.

[33] Refer to chapters II and VI for the effects of air pollutants on health.

[34] US EPA and NHTSA, Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles - Phase 2, Regulatory Impact Analysis, Final Rule. August 2016, EPA-420-R-16-900.

[35] Refer to the first paragraph of the section for the justification argument.

empirical analysis, I do not intend to investigate how effective the CAFE standards are in improving asthma[36] (i.e. CAFE standards are not the predicted variables in the empirical models). Rather, I investigate the effects of vehicle fuel economy on asthma improvement.

5.2 Mediation Analysis and Mediator

Introduced by Baron and Kenny (1986), mediation analysis is now widely used in the field of Psychometrics (or Quantitative Psychology). When psychologists look for the causal link between the independent variables and a dependent variable through an intermediate variable, mediation analysis is the *de facto* method for testing the causal relationship and mechanism (Rucker, Preacher et al. 2011). Such an intermediate variable is called a mediator. The mediator transmits the effect of independent variables onto the dependent variable. MacKinnon, Fairchild et al. (2007), and Rucker, Preacher et al. (2011) provide comprehensive insights of applying mediation analysis in psychologic researches, respectively[37]. In the mediation analysis, the effect of an independent variable[38] on a dependent variable is the direct effect; the effect of the mediator on the dependent variable is the indirect effect of independent variables on the dependent variable.

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[36] The effect of CAFE standards on the overall fuel economy of on-road automobiles is observed clearly from vehicle data. See chapter VII for the results.

[37] MacKinnon details the mediation analysis in his book *Introduction to Statistical Mediation Analysis*, published by Lawrence Erlbaum Associates.

[38] To simplify the illustration, I use the one variable case. The same rationale also applies to any multiple variables case.

The estimation framework of the classical mediation analysis[39] consists of a series of three key regression models: (a) the regression model of the dependent variable on the independent variable (the reduced model); (b) the regression model of the mediator on the independent variable; (c) the regression model of the dependent variable on the independent variable and the mediator (the full model). The indirect effect is the difference of the estimated coefficients of the independent variable between the models of (a) and (c). Causal mechanism is supported if the following conditions are satisfied: (1) the estimated coefficient of the independent variable is statistically significant in (a); (2) the estimated coefficient of the independent variable is statistically significant in (b); (3) the estimated coefficient of the mediator is statistically significant in (c); (4) the magnitude of estimated coefficient of the independent variable in (c) is smaller than the magnitude of estimated coefficient of the independent variable in (a). The estimated coefficient of the independent variable in (c) need not be statistically significant. If it is, that implies an incomplete indirect effect (through mediator) so that the mediator is not the solo mechanism through which the independent variable affects the dependent variable. If it is not, that implies a complete indirect effect so that the mediator is the solo mechanism through which the independent variable affects dependent variable. The regression models can be linear regression models, or nonlinear regression models or a mixture of both (MacKinnon, 2007, Imai, 2010). The assumptions of the mediation analysis including all of the underlined assumptions of all of the regression models in the

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[39] There are two mediation analyses: classical and counterfactual. Since the dissertation only utilizes the classical model, the contents of the counterfactual mediation analysis are left to the readers. Refer to MacKinnon's book of mediation analysis for details.

framework must be met plus an assumption that there is no misspecification of the mediation process.

Mediation analysis is simple to apply in empirical analysis, yet it can provide evidence of a causal relationship between the independent variable and the dependent variable when the assumptions of the model are satisfied. The three individual regressions are estimated separately with no additional model restrictions one another. With mediation analysis, we gain insight and acquire deep understanding about the mechanism of the causal relationship between the independent variable and the outcome.

However, mediation analysis requires that all of the regression models fulfill the underlying model assumptions. It increases the chance of failure to meet assumptions hence invalidating the inference. In addition, if the three regression models are not in the same type (i.e. linear versus non-linear), the mathematical computation estimating the indirect effect and its standard error are difficult to achieve (Imai, 2010). Moreover, the specification of the direct and indirect effects, and the temporal ordering among the three variables (i.e. in the order of the independent variable, the mediator, and the outcome variable) under study must be correct. This could be difficult because after all we are establishing a causal link in the estimation framework. Such specification may be beyond the regression models and require scientific scrutiny.

5.3 Empirical Estimation Framework

I intend to estimate the effect of fuel economy on asthma through the mechanism of reduction of air pollutants using the analytic models of mediation analysis. Following the mediation analysis approach, I consider air pollutants as the mediators that transmit the effects of fuel economy to health outcome – asthma. In particular, the mechanism of mediation effect is illustrated in Figure 5.1 below.

The link between asthma and fuel economy (A) is the direct effect of fuel economy, the links among fuel economy, air pollutants and asthma (B / C) underlie the indirect effect. Based on Baron and Kenny (1986) the steps in estimating the pollutant mediated fuel economy effect on asthma are: (a) Regress asthma on fuel economy; (b) Regress air pollutants on fuel economy; (c) Regress asthma on air pollutants and fuel economy. All the three regression models also control for other covariates. If all estimates are statistically significant, and the magnitude of the estimate from regression in (c) is smaller than the magnitude of the estimate from regression in (a) for fuel economy, such mediation (that fuel economy imposes effect on asthma through air pollutants) can be established.

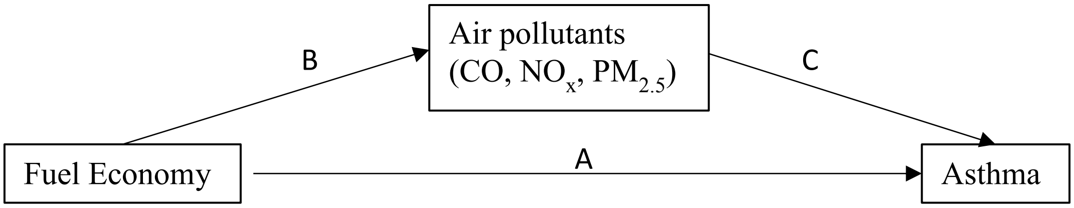

Figure 5.1 The Mediation Analysis Diagram for the Effect of Fuel Economy on Asthma through the Mechanism of Air Pollutants

In the empirical analysis, I look at the variations of asthma, air pollutants, and average vehicle's fuel economy among the US states across a number of years. Following the above mediation analysis principles, I set up the general empirical estimation framework in the following models (equations).

$$asthma = a_1 + \beta_1 \cdot MPG + \delta_1 \cdot Z + \varepsilon \qquad \text{(eq. 5.3.1)}$$

$$P = \alpha_2 + \beta_2 \cdot MPG + \delta_2 \cdot X + \varepsilon \qquad \text{(eq. 5.3.2)}$$

$$asthma = a_2 + \beta_3 \cdot MPG + \gamma \cdot P + \delta_3 \cdot Z + \varepsilon \qquad \text{(eq. 5.3.3)}$$

where *asthma* is the individual asthma status; *MPG* is the average on-road vehicle fuel economy (at state level); *P* is air pollutant level (e.g. $PM_{2.5}$, CO, and NO_2); respectively, *Z* is a set of demographic variables[40] of a given individual; *X* is the covariates of controlling at state level. In models eq. 5.3.1 and eq. 5.3.3, I will use the logistic regression model because the individual's asthma status is dichotomous. In model eq. 5.3.2, I will use ordinary least square (OLS) fixed effects regression model to account for the unobserved time-invariant state level characteristics. Model eq.5.3.1 establishes the direct effect (link A in Figure 5.1) between asthma and fuel economy, model eq.5.3.2 establishes the mediation (link B in Figure 5.1) between the pollutant and fuel economy, model eq.5.3.3 establishes the indirect effect (links B and C in Figure 5.1) between asthma and fuel economy through mediator, respectively.

In this mediation analysis framework, the mediator is the air pollutant. If the hypothesis of improving vehicle fuel economy reducing the asthma occurrences through

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[40] They are the age, gender, race, smoking status, healthcare coverage, income, education, weight, BMI, etc. from the participants of the health surveys.

reduction of air pollutants is true, I shall find (a) statistically significant β_1, and $\beta_1 < 0$; (b) statistically significant β_2, and $\beta_2 < 0$; (c) statistical significant γ; and (d) $|\beta_3| < |\beta_1|$. β_3 need not be statistically significant, and is better if it is not. If all the above conditions hold, the effects of vehicle fuel economy (MPG) on asthma can be compensated significantly by air pollutants. It implies that air pollutants are the mechanism through which the MPG affects asthma. Moreover, if β_2 is not statistically significant, air pollutants are the solo mechanism through which the MPG affects asthma.

In the estimation framework, all three fixed effects regression models must meet the underlying assumptions of the fixed effects regression model: the individual-specific effect is not correlated with the explanatory variables, and the time-varying explanatory variables are not perfectly collinear (i.e. they have non-zero within-variance). In addition, there is no misspecification of the mediation framework (i.e. the causal link fuel economy to air pollutants to asthma). Note that a model of regressing the outcome variable on the mediator is not needed in this framework.

5.4 Restrictions and Potential Problems

In the estimation framework specified in section 5.3, the variables of air pollutants (P), and fuel economy (MPG) are the state-level unweighted average of each year. Such averaging eliminates the between-geographic region (for air pollutants) variations. However, because I can neither attach specific individual car’s MPG at the individual person level, nor attach the air pollutant at the individual person level, this is by far the best alternative.

The available data of asthma are individual persons' survey data, which allows us to model the status of asthma with respect to state-level MPG and/or state-level air pollutant similar to eq.5.3.1 and eq.5.3.3 in a logistic regression setting. The statistical test and inference in mediation analysis are based on the framework that models of eq.5.3.1 and eq.5.3.3 are the same kind of regression model. This allows me to test the direct and indirect effects of MPG on asthma on the individual person data.

The variable of individual asthma status is dichotomous, (i.e. values are either 0 or 1). There are three common regression models for modeling dichotomous dependent variables. They are linear probability model (LPM), logistic regression model, and probit regression model. The lattermost two are nonlinear models with the assumptions that the error terms are in logistic and normal probability distributions, respectively. LPM is not appropriate due to its problem in heteroscedasticity, and failure to restrict the dependent variable within the range of 0 to 1 and to hold the assumption of normally distributed error terms. Logistic and probit models generally give similar results though the probability distribution of the error term of the logistic model has flatter tails that makes the conditional probability of the dependent variable approaching 0 or 1 at a slower rate in the logistic model than in the probit model. I will use the logistic regression model because it allows me to estimates the odds ratio (asthma / non-asthma).

Due to the limitation of the data, our models may suffer the problem of endogeneity. Wherever possible, I use the fixed effects models to account for the unobserved state level time invariant characteristics, and to ameliorate the unobserved heterogeneity problem.

Like all empirical analysis, the availability and quality of data is crucial for the validity of the estimations and the conclusions. Ideally, if I have the perfect data of, at a county-state-and year level, each registered vehicle, air pollutants level, and asthma records of all residents, the results of the analysis will be convincing. However, such data are not readily available for the dissertation. Instead, I retrieve the state-level vehicle registration data, average the air pollutant levels to the state-year level, and use the survey on asthma occurrence. Meanwhile, the quality of the data is better in the later years than in the earlier years. This issue of data quality should be considered when assessing the strength of the evidence in the results.

The assumptions of regression models in all three of the estimation models must be held in order to get consistent estimates. If data are perfect, I shall have no problem in estimating estimates. However, data are far from perfect. In particular, the reduction of pollutants is not only attributed to fuel economy standards, but also is attributed to the emission standards. However, the variation of emission standards is not observed at the state-year level from the available data. This can be ameliorated by using the year dummy as predictors.

The fixed effects model in panel data remedies the unobserved heterogeneity to some degree, but the fixed effects model does not eliminate it entirely. This is noted throughout the analysis.

CHAPTER VI

DATA

This chapter describes the data used in the analyses in the dissertation. There are three main components of the data: vehicle data, air quality data, and health data. Unless otherwise described, all data are downloaded in their original data file formats from the corresponding owner's public internet resources. Source data files are subsequently converted to corresponding SAS data files (working datasets) using the programs developed by me in the statistical software package SAS (SAS Institute Inc., Cary NC). All empirical analyses are carried out on a combined dataset (analysis dataset) merging all of the working datasets by appropriate, typically state and year, identification variables in SAS. All data are state year panel data.

There are three main sources of data. They are the U.S. federal government agencies: Office of Highway Policy Information, Federal Highway Administration (FHWA) of the Department of Transportation (DOT), the Environmental Protection Agency (EPA), and the Center for Disease Control and Prevention (CDC). All data are collected in the US.

The chapter is organized as follows: section 6.1 describes the vehicle data, section 6.2 describes the air quality data, section 6.3 describes the health data from the Behavior Risk Factor Surveillance Survey, section 6.4 describes other data, and section 6.5 describes the data processing procedures.

6.1 Vehicle Data

The dissertation involves three sources of vehicle data: vehicle registrations, fuel consumption, and vehicle miles traveled (VMT).

All vehicle data are from the Highway Statistics Series Publications of the Office of Highway Policy Information, FHWA of the DOT. These data, summarized to the state level in each year, are publicly available from the Internet at the web site of DOT FHWA Highway Statistics Series (HSS).[41] All data are provided in Microsoft Excel files, one data file per year. Within each year, data are summarized at the national level as well as broken down by states and the following functional units. These summarized data are reported to DOT by corresponding states' vehicle regulatory authorities (mainly the Divisions of Motor Vehicles or DMV) every year from the 1980s. Each state keeps individual vehicle's data of the state. These individual vehicle data are not required to be reported to the DOT.

6.1.1 Vehicle Registration Data

The vehicle registration data are under the Vehicles section of the HSS website. In particular, this dissertation concerns two vehicle registration databases: state motor-vehicle registrations (MV-1), and truck and truck-tractor registrations (MV-9). Vehicles are categorized as automobiles (passenger cars, SUVs, minivans, light duty pickup trucks, etc.), buses, and trucks (trailer trucks, farm trucks, etc.). The number of vehicles of each category are recorded in the databases.

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[41] http://www.fhwa.dot.gov/policyinformation/statistics.cfm

Data files of MV-1 and MV-9 from 1995 to 2013 are downloaded and stacked together to form a state-year panel, respectively. Panels of MV-1 and MV-9 are then merged together by state and year to construct the vehicle registration panel (Vehreg_Pool).

The vehicle registration panel consists of the number of vehicles (total, as well as broken down by types of vehicles). In this dissertation buses and trailer trucks are excluded from the analysis. The reasons are the following: 1) the CAFE standards only apply to private passenger vehicles. Buses and trailer trucks are excluded from the policy. My dissertation concerns the effects of CAFE (upon increasing the vehicle fuel economy of the on-road vehicle fleet) on asthma. So, there is not much sense in considering buses and truckers. In calculating the MPG variable, mileage travelled from buses and trailer truckers are, thus, excluded. 2) The MPG variable used in the analysis is based on gasoline. Because buses and trailer trucks mainly use diesel, to use gasoline based MPG, buses and trailer trucks must be excluded (If bus/trailer trucks are included, a gasoline equivalent transforming diesel to gasoline MPG should be used), and 3) Trailer trucks and many buses are highly mobile travelers. They transport cargo and people across states. Thus, the amount of fuel they consume is largely out of their registration states. Therefore, it would not be a good idea to include them in my analysis by state level setting.

6.1.2 Vehicle Mileage Data

The vehicle mileage data are under the Highway Travel section of the HSS website. In particular, this dissertation is concerned with the database of Vehicle-miles of Travel by Functional System (VM-2). Vehicle travel miles are summarized at the national level as well as broken down by different functional systems such as interstate highways, other expressways, principle arterial, minor arterial, etc.

VM-2 data files year from 1995 to 2013 are downloaded and imported as SAS working datasets. Annual data are stacked together to form the vehicle mileage panel (Veh_Miles). The vehicle mileage panel is used to derive the state level fuel economy variable Miles per Gallon (MPG).

6.1.3 Fuel Sales Data

The fuel sales data are under the Motor Fuel section of the HSS website. In particular, this dissertation concerns itself with the database of Total Taxed Fuel Sales (MF-2), Highway Fuel Sales (MF-27) and Non-Highway Fuel Sales (MF-24). Fuels are broken down by gasoline and special fuels: diesel and ethanol (E85 gasoline).

Data files of MF-2, MF24, MF27 from 1995 to 2013 are downloaded and imported as SAS working datasets and merged together by state. Annual data are stacked together to form a state-year fuel sales panel (Fuel_Pool). The fuel sales variables (total fuel sales, gasoline sales, diesel sales and E85 sales) in the fuel sales panel are volumes of sales. The fuel sales panel is used to derive the state level fuel economy variable MPG as described in section 6.1.4.

6.1.4 Fuel Economy Data

The average vehicle fuel economy is derived by dividing the total vehicle miles by gasoline-equivalent gallons[42] sold per state per year. This resembles the fuel economy (MPG) of the average on-road vehicle per state per year. The fuel economy variable is the key predictor variable of the estimation models (eq. 5.3.1 – 5.3.3) specified in Chapter V.

6.2 Air Quality Data

Air quality data are air pollutant measurements. Air pollutant measurement data are obtained from the US EPA[43]. The EPA collects air pollutant measurements via the National Ambient Air Monitoring Program (NAAMP). The program is a network of air monitoring stations for criteria pollutants in each state. The monitoring stations in this network are called the State and Local Air Monitoring Stations (SLAMS). The states must provide the EPA Office of Air Quality Planning and Standards (OAQPS) with an annual summary of monitoring results at each SLAMS monitor, and detailed results must be available to OAQPS upon request. The EPA also calculates and publishes associated aggregate values (eg. 8-hour, daily, annual, etc.) based on the monitoring results of the criteria pollutants. All of the data are available to the public through the EPA Air Quality System (AQS) Data Mart. The AQS Data Mart is a copy of AQS made once per week

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[42] Gasoline-equivalent gallon (GEG) is the amount of alternative fuel it takes to equal the energy content of one liquid gallon of gasoline. In particular, 1 gallon of diesel equals 1.155 gallons of gasoline, and 1gallon of E85 gasoline-ethanol fuel equals 0.734 gallons of gasoline. Conversion factors are provided by the US Department of Energy. http://www1.eere.energy.gov/vehiclesandfuels/epact/fuel_conversion_factors.html.

[43] http://www.epa.gov/airquality/airdata/

accessible to the public through web-based applications. These data include the six criteria pollutants (CO, ground O_3, NO_2, PM, SO_2, and lead).

In this dissertation, I mainly am concerned with the data of the aggregate values of those mobile source criteria pollutants: in particular, weighted annual $PM_{2.5}$, CO and NO_2 measurements. The EPA generates these aggregate values at the county level from the reading of its designated air pollutant monitors. These data are retrieved from the AQS Data Mart download web site[44]. The county level measurements are subsequently averaged weighted by state population to form the state level measurements in each year.

Data files from 1995 to 2013 are downloaded and imported as SAS working datasets. Annual data are stacked together to form the air quality panel. The air quality panel consists of $PM_{2.5}$ measured by the 98th percentile of the daily average (PM1), $PM_{2.5}$ measured by the weighted annual mean (PM2), CO measured by the 2nd highest 1-hour measure (CO1), CO measured by the 2nd highest non-overlapping 8-hour average (CO2), and NO_2 measured by the 98th percentile of the daily max 1-hour measure (NO).

Variables of the air pollutants, CO1, CO2, NO, PM1, and PM2, are the mediators of the mediation analytic models (eq.5.3.2 and eq. 5.3.3) specified in Chapter V.

6.3 Behavior Risk Factor Surveillance Survey Data

This dissertation concerns itself with the health outcomes of asthma and diabetes. Asthma is the outcome variables. Diabetes is chosen in the model as a covariate because people with diabetes have higher rates of asthma and sometimes it becomes tough to

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[44] https://www3.epa.gov/airquality/airdata/ad_rep_mon.html

balance the blood sugar levels and keep it under control. I used the Behavioral Risk Factor Surveillance System (BRFSS) data from the US Center of Disease Control and Prevention (CDC)[45]. The BRFSS is the nation's premier system of health-related telephone surveys that collect state data from US residents regarding their health-related risk behaviors, chronic health conditions, and use of preventive services as well as their demographic characteristics. The subjects are individual adults randomly chosen from states in each survey year. Thus, pooling subject data together form a pooled cross sectional data, not a panel data. However, the average of the variables at state year can be considered as variables of a representative subject of that state year because of the random sampling mechanism. In the empirical analysis of this dissertation, subject characteristic variables are averaged at state year to form the health data panel.

6.3.1 Respiratory Data

Individual asthma prevalence data are obtained from BRFSS. Asthma status is one of the disease conditions surveyed. An individual is identified to currently have asthma or not, along with his or her demographic characteristic and behavioral variables (age, gender, race, smoking, and drinking etc.). I subset the data by including (and/or deriving) the asthma status, Body Mass Index (BMI), BMI Categories (normal, overweight, obese), Income, Gender, Smoking status, Age, Age category (< 65, >=65), whether he or she has healthcare coverage, Weight, Race, and education level. Records are associated with corresponding survey year and the resident state. These variables are

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[45] http://www.cdc.gov/brfss/data_documentation/index.htm

averaged at state year to construct the asthma panel. These variables resemble the demographic characteristics of a representative person of a state in a year. They are used as control variables in the analytic model specified in Chapter V.

6.3.2 Diabetes Data

Diabetes prevalence data are also obtained from BRFSS along with the asthma prevalence data, and processed the same way as asthma data to construct the diabetes panel.

6.4 Other Data

I also obtained macroeconomics data, in particular the Gross Domestic Production (GDP) data, from the US Bureau of Economic Analysis of the Department of Commerce.[46] The macroeconomics data is used to proxy the unobserved economic activities of the state in a particular year. The state year GDP panel consists of the total GDP, manufacturing GDP, and non-agricultural GDP from 2003 to 2011.

6.5 Data Processing

All panel datasets from different sources are together by state and year to construct the analysis data panel for the analytic models specified in Chapter 5. The analysis data panel consists of 48 states (continental states, Hawaii and Alaska are excluded) and years from 2003 to 2011.

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[46] http://bea.gov/iTable/index_nipa.cfm

Federal Information Processing Standards (FIPS) codes of states are utilized as the identification codes in the data merging process. The FIPS codes are standardized numeric or alphabetic codes issued by the American National Standards Institute (ANSI) to ensure uniform identification of geographic entities through all federal government agencies. Because the data of this dissertation are retrieved from different government agencies, using FIPS codes can ensure data consistency across states and counties. Table 6.1 lists such FIPS of states.

CHAPTER VII

SUMMARY STATISTICS AND GRAPHICAL ANALYSIS

This chapter presents the summary statistics of the variables of the data used in this dissertation, and illustrates graphically the trends of the variables of health outcomes, fuel economy, and mobile source air pollutants as well as their correlations over time.

The chapter is organized as follows: section 7.1 presents the summary statistics of the demographic characteristics of the individual respondents in the BRFSS data, and illustrates their changes over time; section 7.2 presents the summary statistics of vehicle fuel economy and air pollutants, and illustrates their correlations at the state level over time; section 7.3 presents the summary statistics of health outcomes (asthma and diabetes) at the state level, and illustrates their changes over time.

7.1 The Demographic Characteristics Variables

The BRFSS data are collected on individual persons (respondents) randomly selected by the survey annually. It contains the variables of the respondent's demographic characteristics as well as the health status such as asthma and diabetes. Variables of state level demographic characteristics (as if an average person of the state) are obtained by averaging individual level variables of these characteristics. These are the variables to be controlled for in the empirical estimation framework as specified in Chapter V section 5.3.

These variables include age, race, gender, education status, income, weight, BMI, smoking status, and health coverage. Asthma is the health outcome variable in the above framework.

The Summary statistics of variables of BRFSS respondents are tabulated in Tables 7.1, and 7.2, with Table 7.2 being the frequency table of the categorical variables of the respondents. Note that these, and subsequent tables and figures, are overall summary data across years and continental states including DC (Alaska and Hawaii are excluded).

Table 7.1 Summary Statistics of Individual Demographic Variables and Health Status

Characteristics	N	Mean	Std. Dev.	Min	Median	Max
Age	4220120	53.50	17.263	18	54	99
Age > 65	4220120	0.284	0.4510	0	0	1
Current Smoker	4231027	0.184	0.3871	0	0	1
Caucasian	4210788	0.854	0.3533	0	1	1
Female	4257465	0.614	0.4868	0	1	1
Has Healthcare coverage	4245745	0.884	0.3203	0	1	1
Education status	4244066	4.792	1.0807	1	5	6
Income level	3665756	5.558	2.1414	1	6	8
Weight (*lb*)	4076456	173.59	42.727	0	170	694
Body Mass Index	4065293	27.81	7.859	4.78	26.6	99.99
Body Mass Index Category	4044405	2.110	0.9024	1	2	4
Currently has Asthma	4232263	0.088	0.2832	0	0	1
Currently has Diabetes	4251353	0.107	0.3097	0	0	1

The mean and median age of the respondents are 53.5 and 54, respectively, in Table 7.1. This indicates that the overall distribution of age in the sample is not skewed.

Meanwhile, 28.17% of them are over the age of 65 as shown in Table 7.2. The median age of the US population is around 38[47] and percentage of age over 65 is around 14.9%[48]. Thus, the survey over-samples elders. People with ages greater than 50 are mostly subject to chronic diseases including asthma and diabetes; thus, the asthma and diabetes prevalence in BRFSS dataset may not reflect the true corresponding prevalence of the US population. This has a great impact in interpreting the results of empirical estimations as the inference may only apply to elder persons.

The median education level is 5, above high school graduate (numeric code 4), and about 90% of the respondents are at least high school graduates. This is higher than the US population educational status with 86.3% at least high school graduated. It implies that the respondents to the surveys are mostly from well-educated middle class families.

Shown in Table 7.2, the percentage of Caucasian of the respondents is 84.4%, and the percentage of female is 61.4%. The percentage of Caucasians in the US population is around 77.1%, and the percentage of female in the US population is around 50.8%.[49] Thus, the BRFSS is sample biased to Caucasian and female.

Income is a very important covariate in most econometrical analyses. Unfortunately, the BRFSS data has a large number (~13.90%) of missing income responses. Thus, the income information in BRFSS is not very reliable.

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[47] From the CIA Facts Book: Median Age of 2014, https://www.cia.gov/library/publications/the-world-factbook/fields/2177.html

[48] From US Census Bureau, July 2015 estimates, https://www.census.gov/quickfacts/table/PST045215/00

[49] From US Census Bureau, July 2015 estimates, https://www.census.gov/quickfacts/table/PST045215/00

Regarding the health condition, shown in table 7.1, the average weight of the respondents is 173.59 lbs, and the median weight is 170 lbs. The mean and median BMI of the respondents are both above the overweight category. However, the mean and median BMI categories are the normal weight (numeric code 2). This implies that the BMI is skewed to the right. In medical literatures, overweight and obese people have higher risk of diabetes. This partially explains the rapid increase in trend of diabetes in Figure 7.5.

Table 7.2 Frequency and Percentage of Individual Demographics Variables

Demographic Characteristics	Category	Numeric Code	Frequency	%
Age > 65	Missing		37345	0.88
	No	0	3020905	70.96
	Yes	1	1199215	28.17
Current Smoker	Missing		26438	0.62
	No	0	3454456	81.14
	Yes	1	776571	18.24
Caucasian	Missing		46677	1.10
	No	0	615625	14.46
	Yes	1	3595163	84.44
Female	No	0	1642040	38.57
	Yes	1	2615425	61.43
Education level	Missing		13399	0.31
	No Schooling	1	6287	0.15
	Elementary	2	137975	3.24
	Some high school	3	277600	6.52
	High school graduate	4	1288872	30.27
	Some college	5	1133935	26.63
	College or more	6	1399397	32.87
Income level	Missing		591709	13.90
	< $10,000	1	203745	4.79
	$10,000 - < $15,000	2	226773	5.33
	$15,000 - < $20,000	3	296102	6.95
	$20,000 - < $25,000	4	365946	8.60
	$25,000 - < $35,000	5	475952	11.18
	$35,000 - < $50,000	6	593708	13.95
	$50,000 - < $75,000	7	604978	14.21
	>= $75,000	8	898552	21.11
BMI category	Missing		213060	5.00
	Under weight	1	1199238	28.17
	Normal weight	2	1452655	34.12
	Over weight	3	1142375	26.83
	Obese	4	250137	5.88

Figure 7.1 illustrates the trends of the demographic variables over time. In Figure 7.1, the *x*-axes in all plots are the *year*. In the figure, Panel (a) shows the trends of age and education level. The *y*-axis on the left is *age* in years, the *y*-axis on the right is the *education level* with 4 being high school graduate, 5 being some college education, and 6 being college graduate or higher. One can observe that the education level is improved over time with average education level being above high school graduate all the time, along with the aging trend (from approx. 47 in 2001 to approx. 55 in 2012) of the respondents. Panel (b) shows the trends of weight and BMI. Consistent with the literature, the average weight and BMI of America has increased over time with average people being over-weight (BMI > 25). Panel (c) plots the smoking status and health coverage of the respondents. The *y*-axis on the left is the percentage of people with some kinds of healthcare coverage, the *y*-axis on the right is the percentage of people who are currently smoking. One can observe the trend that the healthcare coverage has increased over time and the percentage of smokers has decreased over time. Panel (d) shows the percentage of Caucasian and Women of the respondents. One can observe that these characters are stable over time.

In all panels, one can observe that the last two data points (2011 and 2012) are not consistent with the trends. This is due to the change of the survey methods of interviewing from landline phones before 2011 to both landline and cell phones in and after 2011. Generally, cell phone users are younger, more educated, and men. This is out of the scope of this dissertation and therefore not discussed in more detail here. Note that the data point of BRFSS in 2012 is not utilized in the empirical estimation in Chapter VIII because the vehicle data are only up to 2011.

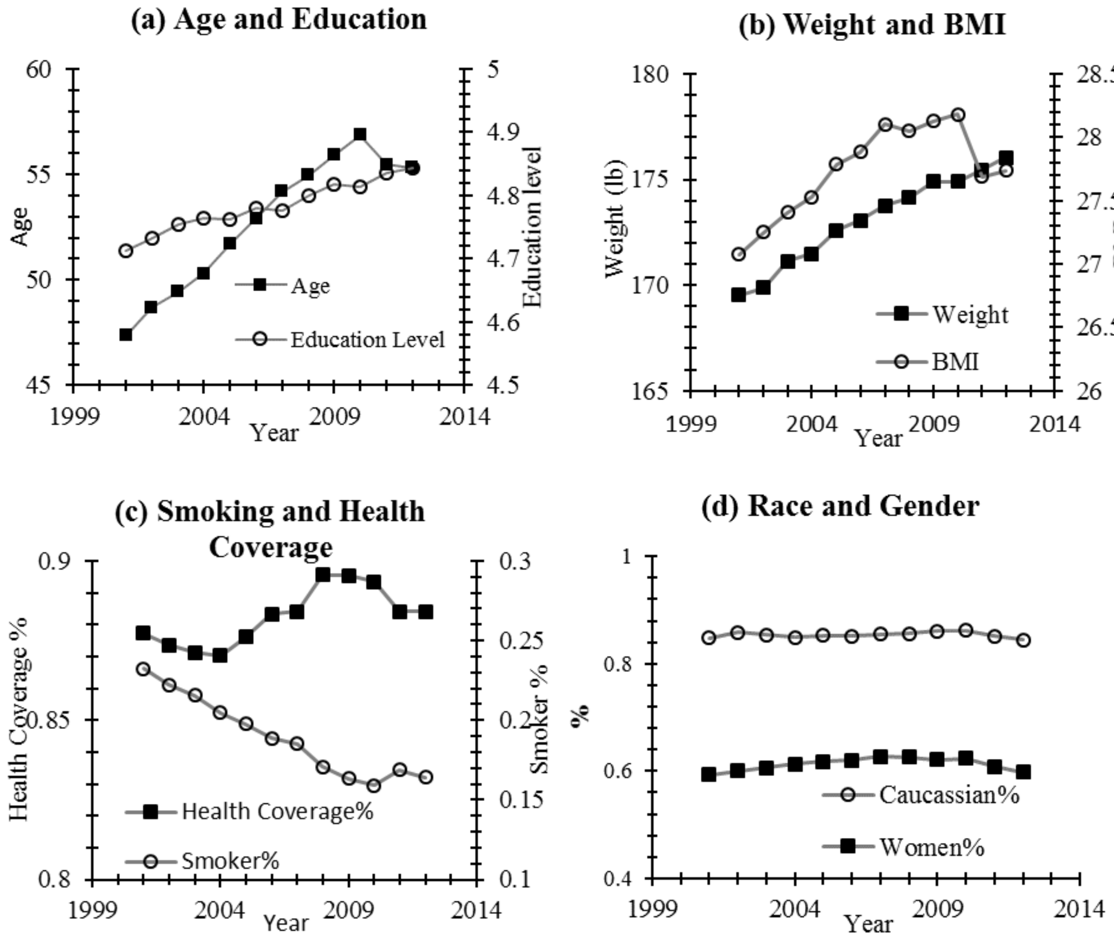

Figure 7.1 Change of Demographics and Characteristics of the Respondents in the BRFSS Survey over Time

Table 7.3 shows the unweighted summary statistics of the demographic at the state level. The variables of individuals' demographics are averaged per state per year, then summarized. The state level demographics treats the state as an average person with these average demographic characteristics. Note that the GDP[50] is in the BRFSS data; however, it is here because it will be the income proxy in the empirical estimations in Chapter VIII.

Table 7.3 Summary Statistics of State-level Demographics Variables

Demographic Characteristics	N	Mean	Std. Dev.	Min	Median	Max
Average age	588	52.71	3.33	44.33	53.28	59.51
Age > 65 proportion	588	0.271	0.058	0.139	0.277	0.424
Current Smoker proportion	588	0.191	0.036	0.088	0.190	0.311
Caucasian proportion	588	0.853	0.096	0.431	0.865	0.983
Female proportion	588	0.612	0.027	0.496	0.611	0.700
Has Healthcare coverage proportion	588	0.883	0.034	0.769	0.887	0.961
Average Education status	588	4.78	0.17	4.18	4.79	5.34
Average Income level	588	5.53	0.373	4.64	5.52	6.36
Average Weight (lb)	588	180.85	12.50	164.83	175.90	217.62
Average Body Mass Index	588	30.14	1.35	26.57	30.46	33.12
GDP ($) - Per Capita*	539	42386.9	16327.1	26612	39374	152167

* Real GDP, chained 2005 US dollars.

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[50] Data are from the US Department of Commerce, Bureau of Economic Analysis.

Table 7.4 Population-weighted Summary Statistics of State-level Demographic Variables

Demographic Characteristics	N	Mean	Std. Dev.	Min	Median	Max
Average age	588	52.57	3.41	44.33	53.21	59.51
Age > 65 proportion	588	0.271	0.059	0.139	0.279	0.424
Current Smoker proportion	588	0.185	0.038	0.088	0.182	0.311
Caucasian proportion	588	0.834	0.069	0.431	0.845	0.983
Female proportion	588	0.615	0.024	0.496	0.615	0.700
Has Healthcare coverage proportion	588	0.878	0.037	0.769	0.882	0.961
Average Education status	588	4.78	0.15	4.18	4.79	5.34
Average Income level	588	5.54	0.32	4.64	5.53	6.36
Average Weight (lb)	588	174.73	4.52	164.83	174.77	191.25
Average Body Mass Index	588	30.19	1.45	26.57	30.54	33.122
GDP ($) - Per Capita*	539	41827.5	7473.6	26612	41694	152167

* Real GDP, chained 2005 US dollars.

The corresponding population-weighted[51] state-level summary statistics of Table 7.3 are tabulated in Table 7.4. Upon being weighted by the population, states are treated equally in the estimation models in Chapter VIII. The unweighted and weighted statistics are not much different.

7.2 Summary Statistics of Vehicle Fuel Economy and Air Pollutants

The summary statistics of vehicle fuel economy and air pollutant levels at state level are tabulated in Table 7.5. These are the unweighted state-level summary statistics.

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[51] Population data are from the US Census Bureau. Population is the July estimates per state per year.

The corresponding population weighted state level summary statistics are tabulated in Table 7.6. Observe that the weighted summaries are not much different (< 10% variation) to unweighted summaries for all variables.

Table 7.5 Summary Statistics of Vehicle Fuel Economy and Air Pollutants

Variable	N	Mean	Std. Dev.	Min	Median	Max
Vehicle Fuel Economy						
Average fuel economy (MPG)	539	22.42	2.90	15.43	22.06	40.97
Air Pollutant Levels						
PM2.5 - the 98%ile of the daily average (PM1)	588	27.73	6.77	12.38	27.28	65.50
PM2.5 - the Weighted Annual Mean (PM2)	588	10.64	2.42	5.46	10.55	17.06
CO - the 2nd highest 1-hour measure (CO1)	569	3.77	2.82	0.20	3.32	33.50
CO - the 2nd highest non-overlapping 8-hr avg. (CO2)	569	2.23	1.52	0.30	2.05	24.30
NO2 - the 98%ile of the daily max 1-hr measure (NO)	560	44.83	14.41	10	43.56	182

Table 7.6 Population Weighted Summary Statistics of State Level Variables

Variable	N	Mean	Std. Dev.	Min	Median	Max
Fuel Economy						
Average fuel economy (MPG)	539	21.83	2.11	15.43	22.06	40.97
Air Pollutant Levels						
PM2.5 - the 98%ile of the daily average (PM1)	588	28.89	6.71	12.38	28.91	65.50
PM2.5 - the Weighted Annual Mean (PM2)	588	11.20	2.14	5.46	11.09	17.06
CO - the 2nd highest 1-hour measure (CO1)	569	3.57	2.34	0.20	3.35	33.50
CO - the 2nd highest non-overlapping 8-hr avg. (CO2)	569	2.15	1.28	0.30	2.02	24.30
NO2 - the 98%ile of the daily max 1-hr measure (NO)	560	48.19	12.95	10	46.71	182

The first step of the empirical analysis of my dissertation is to look for negative correlations between the improvement of vehicle fuel economy and the reductions of air pollutants. The empirical evidence of such correlation is apparent as illustrated in Figures 7.2 through 7.4.

In figure 7.2, I plot the vehicle fuel economy (in the unit of miles per gallon or mpg) and $PM_{2.5}$ (the 98th percentile of the daily average) versus years in different panels, by the US National in panel (a), by different census regions in panels (b) through (e), or by the State of California in panel (f), respectively. In each panel of the figure, the *x*-axis is the year, the *y*-axis on the left is the pollutant level for $PM_{2.5}$ measured at $\mu g/m^3$, the *y*-axis on the right is the vehicle fuel economy measured at *mpg* – miles per gallon. In all panels of the figure, one can observe the clear patterns that vehicle fuel economy improves marginally, yet steadily over time (from 2001 to 2011), the $PM_{2.5}$ level decreases significantly over time (from 2001 to 2012), and negative correlations between vehicle fuel economy and $PM_{2.5}$ across all geographic regions. This correlation is visually clear in all panels.

Meanwhile, I run a Pearson correlation test on the correlation between vehicle fuel economy and $PM_{2.5}$ over time. Table 7.7 lists the Pearson correlation coefficients and *p*-values of their statistical significance between vehicle fuel economy and $PM_{2.5}$, by the US, different census regions, and California. One can observe that the correlation coefficients are all negative, and highly statistically significant (all *p*-values of the correlation coefficients < 0.0001). It is stronger in the State of California. This implies a convincing negative correlation between vehicle fuel economy and $PM_{2.5}$. This statistically significant negative correlation is also observed in most US states, 36 out of the 49 continental states and the District of Columbia show negative correlations (results shown in Appendix C).

Table 7.7 Pearson Correlation between $PM_{2.5}$ (98th Percentile of the Daily Average) Level and Vehicle Fuel Economy

Geographic Region		Pearson Correlation Coefficient	*p*-value
US National		-0.1985	< 0.0001
Census Regions	Northeast	-0.1102	< 0.0001
	South	-0.0428	< 0.0001
	Midwest	-0.1361	< 0.0001
	West	-0.3906	< 0.0001
California		-0.6633	< 0.0001

Figure 7.3 repeats the same plots in Figure 7.2 but with vehicle fuel economy and NO_2. The left *y*-axis is the level of NO_2 measured at *ppb* (1 ppb = 1/000 *ppm*). Generally, the patterns of the decreased trend of NO_2, the increased trend of vehicle fuel economy, and the negative correlation between vehicle fuel economy and NO_2 level over time are also observed except in the South region, where the correlation is positive. Table 7.8 shows the results of Pearson correlation tests between vehicle fuel economy and NO_2 by the US, by census regions, and by the State of California. This statistically significant negative correlation is also observed in most US states, 31 out of the 49 continental states and the District of Columbia show negative correlations (results shown in Appendix A-3)

Table 7.8 Pearson Correlation between NO_2 Level and Fuel Economy

Geographic Region		**Pearson Correlation Coefficient**	***p*-value**
US National		-0.0846	< 0.0001
Census Regions	Northeast	-0.1611	< 0.0001
	South	0.1001	< 0.0001
	Midwest	-0.1819	< 0.0001
	West	-0.1747	< 0.0001
California		-0.7356	< 0.0001

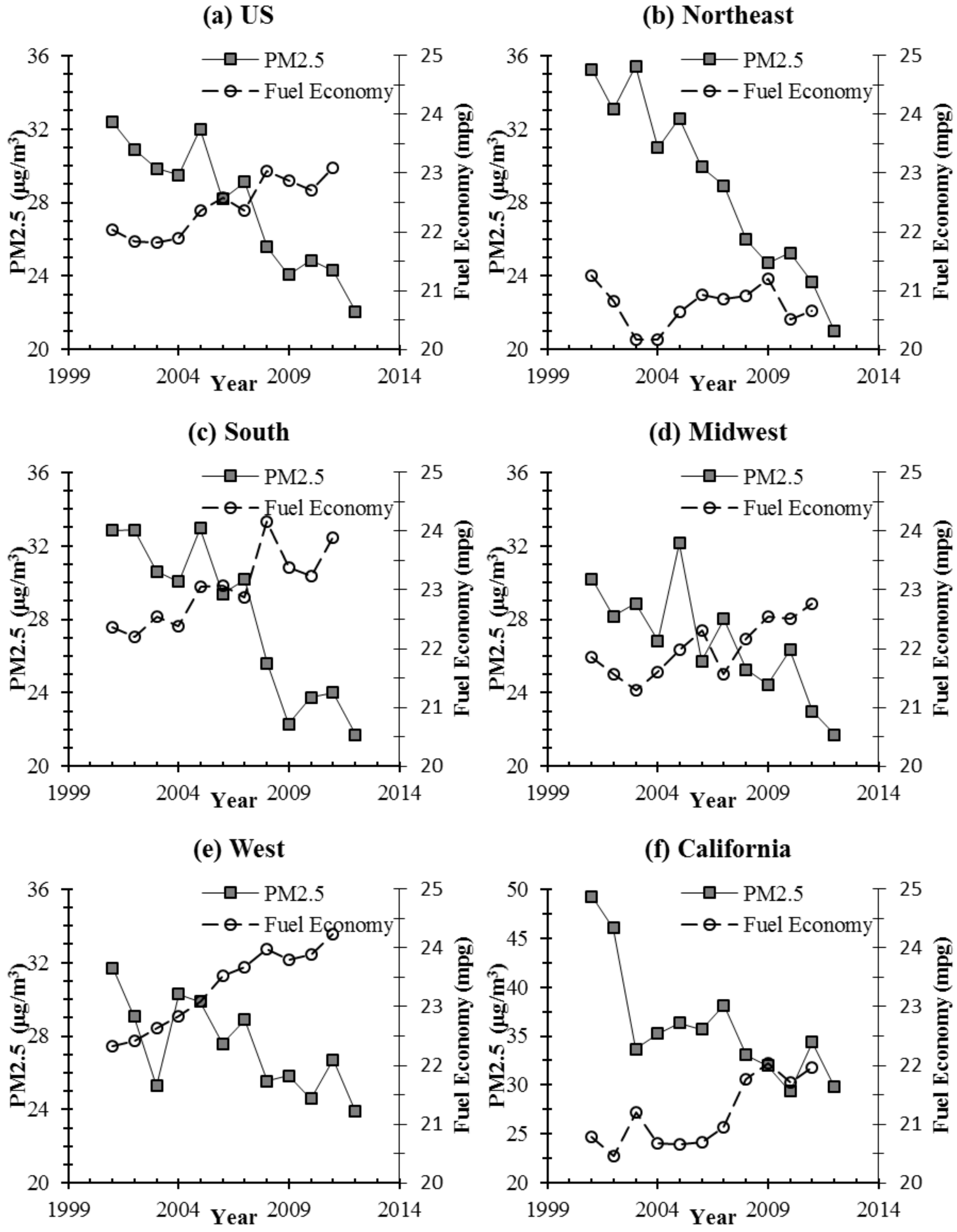
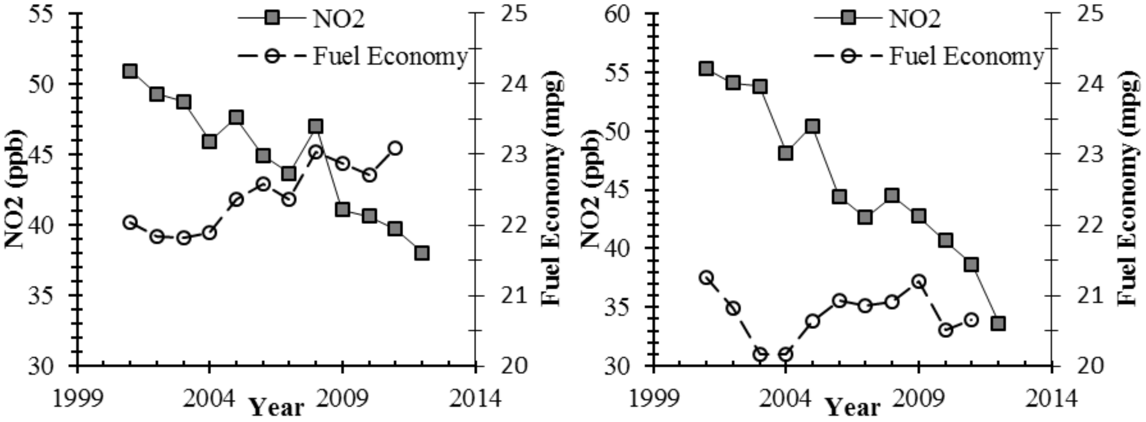
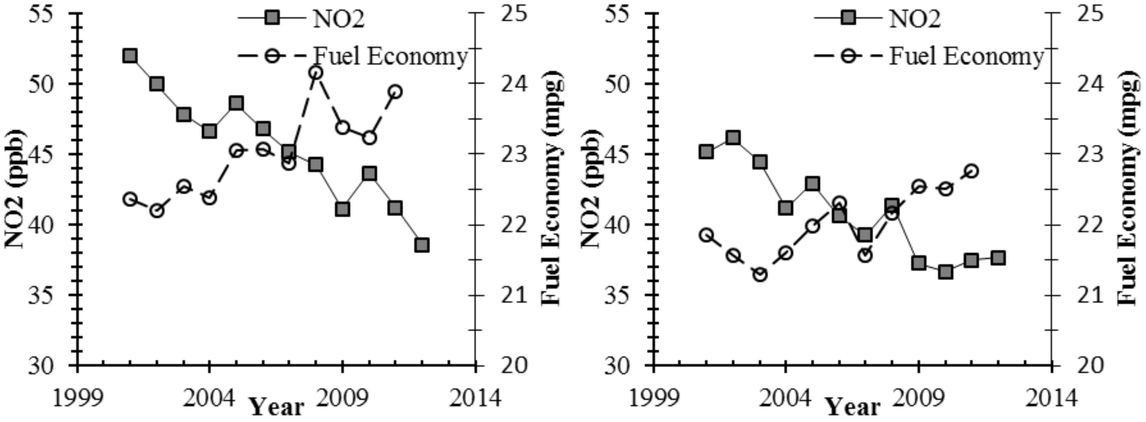


Figure 7.2 PM2.5 (98th Percentile of the Daily Average) vs Fuel Economy by Regions

(a) US (b) Northeast



(c) South (d) Midwest



(e) West (f) California

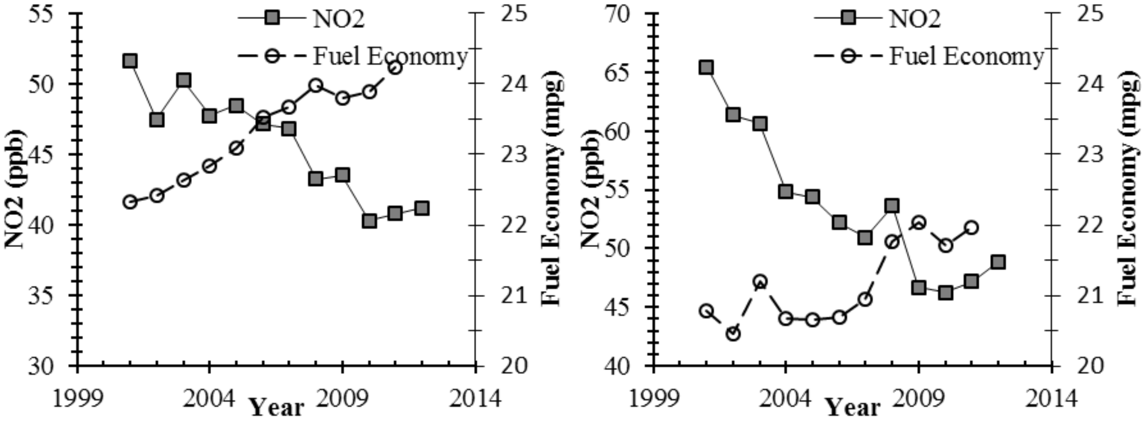
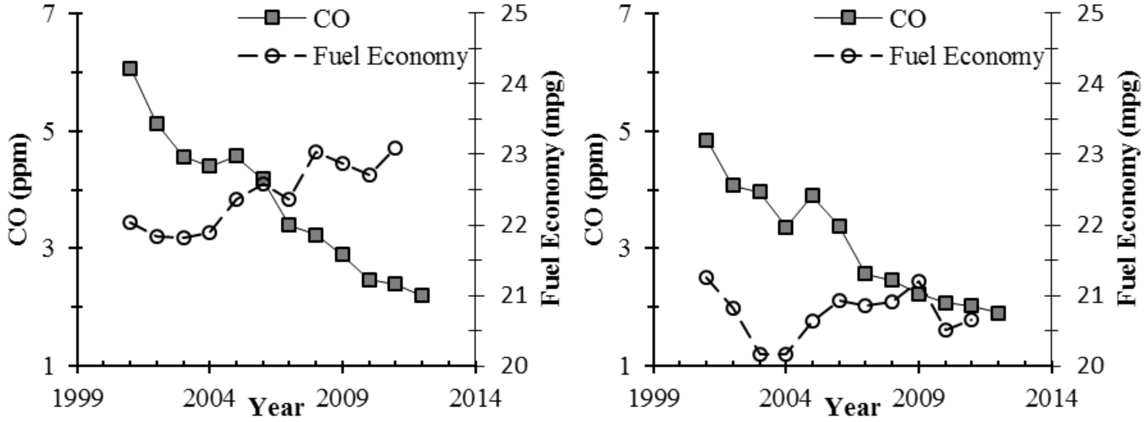


Figure 7.3 NO_2 vs Fuel Economy by Regions

Figure 7.4 repeats the same plots in Figure 7.2 but with vehicle fuel economy and CO (2nd highest 1-hour measurement). The left *y*-axis is the level of NO_2 measure at ppm The corresponding Pearson correlation coefficients are tabulated in Table 7.9. Although one can also observe visually the decreased trend of CO level, the increased trend of vehicle fuel economy, and the correlation between vehicle fuel economy and CO, the results of the Pearson correlation test show different directions: with negative correlation coefficients in the Northeast, West and California, but positive correlation coefficients in the US National level, South, and Midwest. However, this statistically significant negative correlation is also observed in most US states, 33 out of the 49 continental states and the District of Columbia show negative correlations.

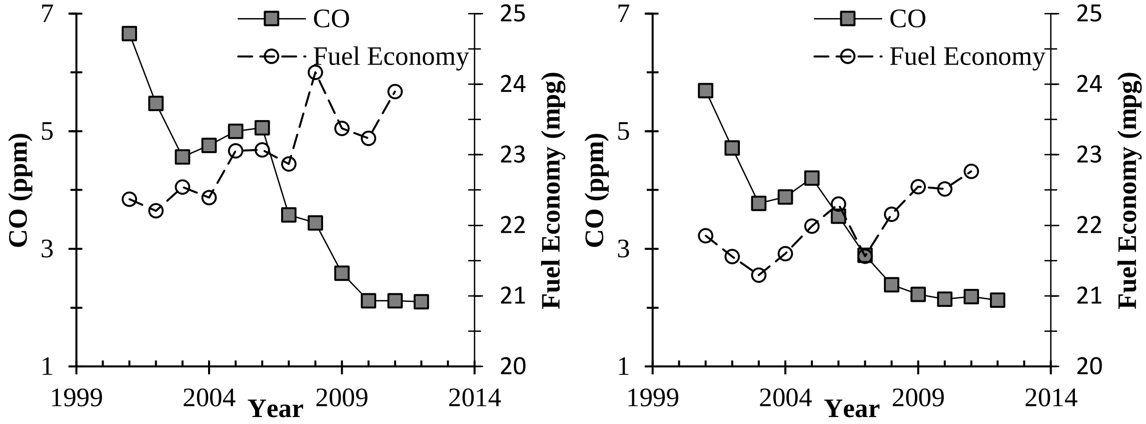
Table 7.9 Pearson Correlation between CO (2nd Highest 1-hour Measurement) Level and Fuel Economy

Geographic Region		Pearson Correlation Coefficient	*p*-value
US National		0.0147	< 0.0001
Census Regions	Northeast	-0.3050	< 0.0001
	South	0.0754	< 0.0001
	Midwest	0.1153	< 0.0001
	West	-0.3052	< 0.0001
California		-0.5321	< 0.0001



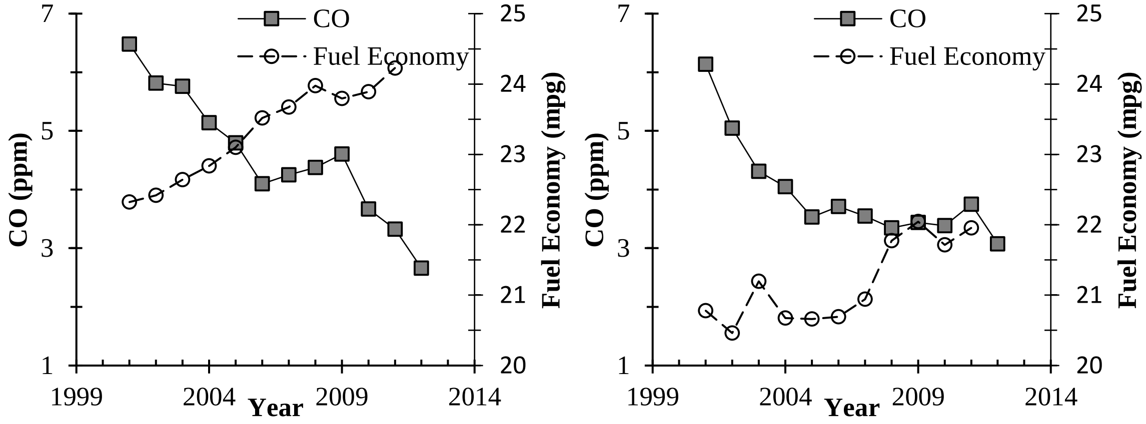
(a) US

(b) Northeast



(c) South

(d) Midwest



(e) West

(f) California

Figure 7.4 CO (2nd Highest 1-hour Measurement) vs Fuel Economy by Regions

Note that in this chapter the correlations between vehicle fuel economy and the pollutants ($PM_{2.5}$, NO_2, or CO respectively) do not control for any other variables, they may not reflect the true relationship between vehicle fuel economy and these pollutants., The empirical estimation models assessed in Chapter VIII control for covariates. Also note that air pollutant data in 2012 are not utilized in the empirical estimation in Chapter VIII because the vehicle data are only up to 2011.

7.3 Asthma and Diabetes

Asthma and diabetes statuses are collected in BRFSS. As described in section 7.1, BRFSS collects individual respondent data. The summary statistics of the asthma and diabetes are tabulated in Tables 7.10 and 7.11 with the latter being the frequency table. Asthma is the health outcome variable concerned in my dissertation. The diabetes is one of the covariates to control for. They are subsequently averaged to the state level for the analysis purpose of my dissertation.

Table 7.10 Summary Statistics of Health Status

Health Outcome	N	Mean	Std. Dev.	Min	Median	Max
Currently has Asthma	4232263	0.088	0.2832	0	0	1
Currently has Diabetes	4251353	0.107	0.3097	0	0	1

Table 7.11 is the frequency table of asthma and diabetes of the BRFSS respondents. From the table, one can observe that about 8.74% of them have asthma and 10.73% of them are diabetic.

Table 7.11 Frequency and Percentage of Asthma and Diabetes

Health Status	Category	Numeric Code	Frequency	%
Has Asthma	Missing		25202	0.5919
	No	0	3860214	90.669
	Yes	1	372049	8.7387
Has Diabetes	Missing		6112	0.1436
	No	0	3794570	89.128
	Yes	1	456783	10.729

The second step of the dissertation is to seek for the positive correlation between air pollutants and the health outcome asthma. In Figure 7.5, I plot the proportion of persons who suffered asthma and diabetes versus year, by the US national level, different census regions, or by the State of California, respectively. This is the unadjusted (to other factors) rates of asthma and diabetes. Observe that the unadjusted asthma rate increases slightly over time in all plots. In the first though, it gives the impression that asthma is negatively associated with the air pollutants (recall in Figures 7.2 the $PM_{2.5}$ decrease largely over time). This does not support my hypothesis. However, observe that the trend of unadjusted rate of diabetes, a disease not caused acutely by air pollutants, [52] increases more steeply over time. This gives me a thought that the slight increase of asthma over time may be due to other reasons, and it may in fact be negatively correlated to air pollutants after controlling for these relevant covariates (reasons). Because one must see health professionals to be diagnosed with asthma, and the insurance coverage creates incentive for one to see the health professionals, the variation of asthma over time may

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[52] There are recent studies that suggest a possible relationship between exposure to air pollutants and type 2 diabetes mellitus; however the causal link is not established.

partly reflect the variation of healthcare coverage. In fact, there is an increase trend of healthcare coverage over time as shown in Figure 7.1 panel (c). Indeed, healthcare coverage indeed is highly statistically significantly correlated to asthma (Pearson correlation coefficient = 0.0024, *p*-value < 0.0001). Meanwhile, recall that as described in section 7.1 the BMI is skewed to the right. In medical literatures, overweight and obese people have higher risk of diabetes. This also partially explains the rapid increase trend of diabetes in Figure 7.5. This also potentially affects the asthma prevalence.

Tables 7.12 and 7.13 are the unweighted and population weighted summary statistics, respectively, of individual asthma and diabetes averaged to the state level. The mean and median between them are not much different (<5% variation).

Table 7.12 Unweighted Summary Statistics of State-level Asthma and Diabetes Prevalence

Health Outcome	N	Mean	Std. Dev.	Min	Median	Max
Currently has Asthma portion	588	0.087	0.011	0.053	0.086	0.124
Currently has Diabetes portion	588	0.102	0.027	0.044	0.100	0.181

Table 7.13 Population Weighted Summary Statistics of State-level Asthma and Diabetes Prevalence

Health Outcome	N	Mean	Std. Dev.	Min	Median	Max
Currently has Asthma portion	588	0.086	0.010	0.053	0.085	0.124
Currently has Diabetes portion	588	0.105	0.026	0.044	0.105	0.181

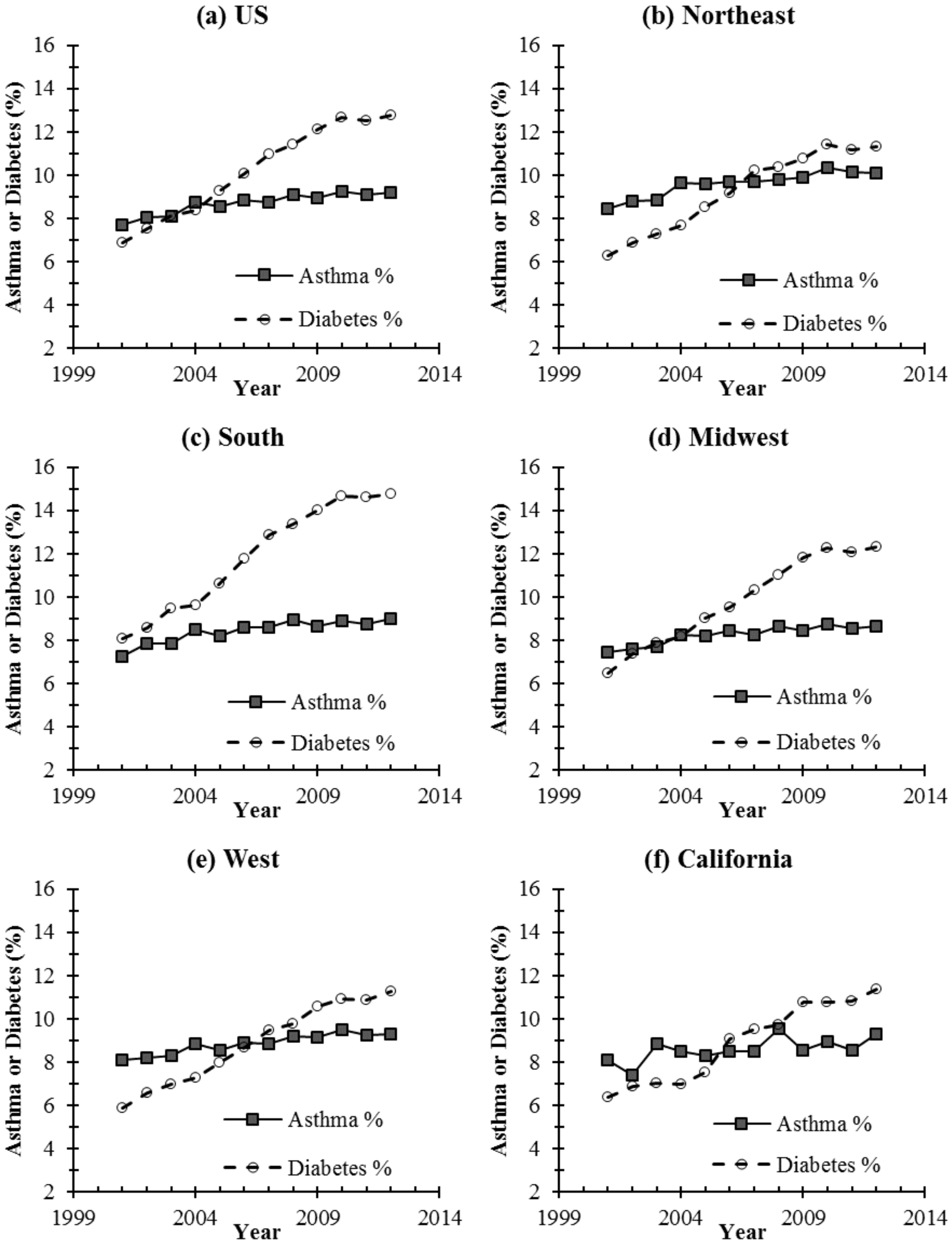

Figure 7.5 Asthma and Diabetes Prevalence

In this chapter, in addition to tabulate summary statistics, I conduct graphical analyses to visualize trends of changes as well as the correlations among fuel economy, pollutants (e.g. $PM_{2.5}$, CO and NO_2), and health outcome (asthma) using vehicle data, air quality data, and Behavioral Risk Factor Surveillance System (BRFSS) data. The results show evidence of the improvement of vehicle fuel economy, air pollution, and a slight increase of asthma prevalence over time. The correlations between vehicle fuel economy and air pollutants can be observed visually and are verified by Pearson correlation. However, the correlations between air pollutants and asthma are not clear due to lack of control for confounders. In the empirical estimation framework described in Chapter VIII, I seek to control for demographics and subject characteristics variables.

I also find that the BRFSS surveys more Caucasians and females, so inference from the empirical analysis needs to be carefully examine when applying to the US population. Nevertheless, the data are in very good quality and are ready for model estimation.

CHAPTER VIII

ECONOMETRIC MODEL ESTIMATION

This chapter presents the results of the model estimations. The chapter is organized as followed: section 8.1 presents estimates of the logistic regression models of asthma on fuel economy after controlling for the demographic and health status on the individual BRFSS data. Section 8.2 presents estimates of fixed effects models of pollutants on fuel economy after controlling for state level variables on the state-year panel data. Section 8.3 presents estimates of the logistic regression models of asthma on fuel economy and pollutants after controlling for the demographic and health status on the individual BRFSS data. Section 8.4 presents the results of assessing the impact of missing data on the model estimates. Section 8.5 discusses the misspecification, unobserved variables, and other issues that may invalidate the conclusion. Section 8.6 concludes the findings of the empirical analysis.

In Chapter V, I prescribe the empirical estimation framework in the following models (equations).

$$asthma_{i,s,t} = a_1 + \beta_1 \cdot MPG_{s,t} + \delta_1 \cdot Z_{i,s,t} + \varepsilon \qquad \text{(eq. 8.1)}$$

$$P_{s,t} = \alpha_2 + \beta_2 \cdot MPG_{s,t} + \delta_2 \cdot X_{s,t} + \varepsilon \qquad \text{(eq. 8.2)}$$

$$asthma_{i,s,t} = a_2 + \beta_3 \cdot MPG_{s,t} + \gamma \cdot P_{s,t} + \delta_3 \cdot Z_{i,s,t} + \varepsilon \qquad \text{(eq. 8.3)}$$

where *asthma* is the individual person's asthma status; *MPG* is the average on-road vehicle fuel economy (at state level); *P* is air pollutant level (e.g. $PM_{2.5}$, CO, and NO_2); respectively, *Z* is a set of demographic variables of a given individual; X is the covariates of controlling at state level. The subscript *i* represents an individual person, *s* presents a state, and *t* represent a year. Models of eq. 8.1 and eq. 8.3 are both estimated at the individual-year level, not the state-year level. Model of eq. 8.2 is estimated at the state-year level.

In the BRFSS data, asthma status is a dichotomous variable. Thus, I choose logistic regression models for estimations in eq. 8.1 and eq.8.3, respectively. In the logistic regression models, the asthma status is modeled as the odds of having asthma (the probability of having asthma divided by the probability of not having asthma).

8.1 Modeling Asthma on Vehicle Fuel Economy

Based on the estimation framework prescribed in Chapter V, the first step is to regress asthma status (Yes/No) on the vehicle fuel economy (MPG) at the state level controlling for individual respondent's demographic characteristics (age, race, gender, education, and income, etc.) and health status (smoking condition, BMI, diabetic status, and health coverage, etc.) in a logistic regression model (e.q.8.1). This model is the reduced model. The variables controlled for represent the effects on asthma other than fuel economy. They are not the variables to be inspected in my dissertation, and therefore I will not discuss their effects on asthma.

The nature of the BRFSS data is a pooled cross-sectional dataset across different years[53] hence the logistic regression model is carried out on all individual respondents across all years. Because the income and education are categorical variables, to avoid non-linear effects, I create dummy variables for the categories, respectively. Table 8-1 summarizes the estimated coefficients of predictors and test statistics from different logistic models of asthma status on different predictors. All models control for the respondent's demographic characteristics (age, race, gender, education, and income, etc.) and health status (smoking condition, BMI, diabetic status, and health coverage, etc.) as well as year fixed effects. They are only different in the combination of income and education variables. For discussion purposes, only the estimates of vehicle fuel economy, income and education are presented in the table.

In Table 8.1, all models have statistically significant[54] (p-value < 0.0001) and negative coefficients in vehicle fuel economy, indicating a statistically significantly negative effect of vehicle fuel economy on asthma status. This implies that a higher vehicle fuel economy decreases asthma prevalence. This is consistent with my hypothesis that improving vehicle fuel economy will foster health benefit in asthma.

Comparing the models A through D, one can observe that the estimated coefficients of vehicle fuel economy are similar in these models, with less than 10% difference, except in model C. The difference between C and others is that in model C, the non-linear effects of education and income are not specified. As shown in the

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[53] Refer to Chapter VI for the details of BRFSS data.

[54] Benchmark alpha level is set to be 0.05 for statistical significance throughout the dissertation.

coefficients of education dummies in model A, the sign of the coefficients of No education and High School education are reversed to the other categories. Thus, there are non-linear effects in education levels. Therefore, the coefficient of vehicle fuel economy is much different to other. I decided to use model A as the baseline model specification for assessing the dissertation hypothesis. In model A, the coefficient of vehicle fuel economy is - 0.00957, which implies an effect of $e^{-0.00957}$ or equivalent to a 1% decrease in the odds (of having asthma vs not having asthma) per 1 mpg increase in vehicle fuel economy, *ceteris paribus*.

Table 8.1 Estimates of Logistic Regression Models [a,b,c]

		A	B	C	D	E
Vehicle Fuel Economy (MPG)		-0.00957	-0.00931	-0.00932	-0.01016	-0.01007
		0.00084	0.00084	0.00084	0.00084	0.00084
		< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Income Level [d]	10 - < 15k	-0.20740	-0.21483	-0.21519		
		0.00949	0.00948	0.00948		
		< 0.0001	< 0.0001	< 0.0001		
	15 - < 20k	-0.39236	-0.40540	-0.40595		
		0.00925	0.00921	0.00922		
		< 0.0001	< 0.0001	< 0.0001		
	20 - < 25k	-0.52325	-0.54138	-0.54222		
		0.00909	0.00901	0.00905		
		< 0.0001	< 0.0001	< 0.0001		
	25 - < 35k	-0.66909	-0.68867	-0.68964		
		0.00891	0.00878	0.00886		
		< 0.0001	< 0.0001	< 0.0001		
	35 - < 50k	-0.77444	-0.79274	-0.79367		
		0.00884	0.00866	0.00880		
		< 0.0001	< 0.0001	< 0.0001		
	50 - < 75k	-0.83895	-0.85371	-0.85441		
		0.00908	0.00889	0.00905		
		< 0.0001	< 0.0001	< 0.0001		
	>= 75k	-0.90888	-0.92009	-0.92020		
		0.00898	0.00880	0.00895		
		< 0.0001	< 0.0001	< 0.0001		
Income in Cardinal Categories (1 -8) [e]					-0.12665	-0.12739
					0.00108	0.00105
					< 0.0001	< 0.0001
Below College vs College and Above			-0.00786			-0.03082
			0.00489			0.00482
			0.10801#			< 0.0001
Education Level [f]	- No	-0.16625				
		0.05819				
		0.00428				
	- Elementary School	0.03245				
		0.01204				
		0.00702				
	- Secondary School	0.15488				
		0.00863				
		< 0.0001				
	- High School	-0.09786				
		0.00573				
		< 0.0001				
	- Some College	0.04424				
		0.00550				
		< 0.0001				
Education in Cardinal Categories [g] (1-6)				0.00291	0.00732	
				0.00215	0.00214	
				0.17567#	0.00063	

Footnotes of the table

a. Modeling the outcome of Asthma (Yes/No) controlling for respondent's demographic characteristics (age, race, gender, income, and education, etc.), health status (smoking condition, Body Mass Index, diabetic condition, and health coverage, etc.), and year as a fixed effect (compared to 2011).
b. Model statistics are listed, per predictor, as estimated coefficient, standard error of the estimated coefficient, and *p*-value of the Wald's test statistics of the significance of coefficient, respectively. Estimates that are not statistically significant at 5% level are marked with #. Estimates of the full set of covariates are presented in Appendix A-4.
c. The states of Alaska, Hawaii, and District of Columbia are excluded from the models.
d. Base income level is ≤ $10,000. Unit is in chained (2005) US dollars.
e. Refer to Table 7-2 for the corresponding coding of income level.
f. Base education level is college and above.
g. Refer to Table 7-2 for the corresponding coding of education level.
N = 3147864 in all models here.

8.2 Modeling Pollutants on Vehicle Fuel Economy

The next step is to assess whether the mobile source air pollutants are associated with vehicle fuel economy. This is accomplished by modeling mobile source air pollutants on vehicle fuel economy (e.q.8.2 of the framework) to detect whether the coefficient of vehicle fuel economy is statistically significant. The mobile source air pollutants are the results of driving and human activities; there is not much a sound reason to believe an individual person's characteristics determine the mobile source air pollutants. Therefore, it is not appropriate to incorporate individual person data to model air pollutants on vehicle fuel economy.

I use the state-level panel of air pollutants and vehicle data to detect the effects of vehicle fuel economy on air pollutants. The air pollutants are fine Particulate Matters ($PM_{2.5}$), carbon monoxide (CO), and Nitrogen Dioxide (NO_2). The panel data consists of 50 US states and the District of Columbia from 2001 to 2011.

The fixed effects model is used to model $PM_{2.5}$, CO, and NO_2 on vehicle fuel economy controlling for the per capita GDP (for economic activities), number of vehicles, and state population. The fixed effects model controls for the time-invariant state level variables so that the unobserved heterogeneity problem is alleviated.

Table 8.2 summarized the estimated coefficients of predictors and test statistics from the models of $PM_{2.5}$, CO, and NO_2 on vehicle fuel economy along with or without controlling for the state level variables per capita GDP (for economic activities), number of vehicles, and state population. From the table one can observe that the coefficients of vehicle fuel economy are all negative, implying that the increasing the vehicle fuel economy will decrease the three air pollutants. This is consistent with the dissertation hypothesis that improving vehicle fuel economy has positive impact on the air quality.

Table 8.2 Estimates [a,b,c] of Fixed Effects Model of Pollutants on Vehicle Fuel Economy Controlling for State-level Covariates

	Dependent Variable					
	$PM_{2.5}$		**CO**		**NO_2**	
Predictors						
Vehicle Fuel Economy (MPG)	-0.9762 0.2410 < 0.0001*	-0.7885 0.2411 0.0012*	-0.2748 0.1032 0.0081*	-0.1798 0.1027 0.0807	-1.0606 0.5806 0.0686	-0.7929 0.5912 0.1807
GDP, per Capita ($)		10587.34 13743.22 0.4416		-8259.73 6241.692 0.1866		-15531.6 32713.75 0.6352
Population		-0.0332 0.0078 < 0.0001*		-0.0139 0.0032 < 0.0001*		-0.0425 0.0186 0.0228*
Number of Vehicles (Millions)		0.1865 0.4915 0.7046		-0.0913 0.2031 0.6534		0.3434 1.1656 0.7685

Footnotes of the table

a. Modeling pollutants Particulate Matter ($PM_{2.5}$), Carbon Monoxide (CO), and Nitrogen Dioxide (NO), respectively.

b. Model estimates are listed as estimated coefficient, standard error of estimate, and p-value of the t-test statistics, respectively. *: Statistically significant at the 5% level.
c. The states of Alaska, Hawaii, and the District of Columbia are excluded from the models.
N = 528 for all models

However, one can also observe that the effects of vehicle fuel economy is only statistically significant in the models $PM_{2.5}$ on vehicle fuel economy with or without controlling for the state level variables, and CO on vehicle fuel economy without controlling for the state level variables. Evidence of such effects is relatively weak in CO and NO_2. However, when using a Balanced Panel (only include data from those counties appeared in all years), the effects are stronger. See section 8.5's discussion on Tables 8.7-8.9 for details. Nevertheless, this provides some empirical evidence that improving the vehicle fuel economy may reduce the mobile source air pollutants.

8.3 Modeling Asthma on Vehicle Fuel Economy and Pollutants

The last step of the empirical analysis is to determine whether air pollutants are mediators that transmit the effects of vehicle fuel economy on individual's asthma, also known as the mediation effect. In order to claim the mediation effect, there are two criteria to meet: 1. the magnitude of the coefficient of vehicle fuel economy decreases when adding air pollutants to the model of asthma on vehicle fuel economy; 2. the coefficients of air pollutants in such a model are statistically significant. In addition, the mediation effect of air pollutants is a complete effect (that air pollutants are the solo mediator) if the coefficient of vehicle fuel economy is not statistically significant, or a partial effect (that there exists other mediators) if the coefficient of vehicle fuel economy is statistically significant.

Table 8.3 summarizes the results of estimations of the models similar to the model A with adding $PM_{2.5}$, CO, NO_2 individually and jointly to test the mediation effects of pollutants separately and jointly, respectively. These models are the full models. They correspond to model 1 to 4 in the table. In the table, one can observe that the coefficients of air pollutants are statistically significant in all models. And, in each model, the absolute values of the coefficient of vehicle fuel economy is statistically significant and smaller than that of the coefficient (0.00957) of vehicle fuel economy in the baseline model. This implies that these air pollutants are mediators that partially transmit the effects of vehicle fuel economy to asthma status. In model 4, the three air pollutants are jointly statistically significant, the absolute values of the coefficient (0.00577) of vehicle fuel economy is statistically significant and smaller than that of the coefficient (0.00957) without air pollutants. This gives strong evidence that the joint three air pollutants are mediators with partial mediation effects.

Compared to model 4 and A, the indirect effect of the three air pollutants accounts for about 39.7%[55] of the effects of vehicle fuel economy on the log odds ratio.

I also conduct the mediation analyses with the linear probability models, and the probit regression models, respectively. Results of corresponding estimations are summarized in Appendix D and E, respectively. The results are consistent with what those observed in the logistic regression models: coefficients of Vehicle Fuel economy are negative and statistically significant in the reduced model and the full model,

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[55] Calculated by $\frac{-0.00957-(-0.00577)}{-0.00957} \approx 39.7\%$

respectively; the magnitude of the coefficient in the full model is smaller than the coefficient in reduced model. Thus, pollutants are shown to be the mechanism, individually or jointly, that mediate the effect of Vehicle Fuel Economy on Asthma.

Table 8.3 Logistic Regression Estimates [a,b] of Asthma on Fuel Economy and Pollutants, Controlling for Demographic and Health Variables [c]

Predictor	1	2	3	4	A[d]
Vehicle Fuel Economy (MPG)	-0.00699 0.00086 < 0.0001	-0.00825 0.00085 < 0.0001	-0.00816 0.00086 < 0.0001	-0.00577 0.00090 < 0.0001	-0.00957 0.00084 < 0.0001
$PM_{2.5}$	0.00514 0.00037 < 0.0001			0.00258 0.00041 < 0.0001	
CO		0.00126 0.00094 0.18015#		0.00552 0.00117 < 0.0001	
NO_2			0.00114 0.00013 < 0.0001	0.00050 0.00014 0.00037	

Footnotes of the table

a. Model statistics are listed as estimated coefficient, standard error of the estimated coefficient, and *p*-value of the Wald's test statistics of the significance of coefficient, respectively. Estimates that are not statistically significant at 5% level are marked with #. Estimates of the full set of covariates are presented in Appendix A-5.

b. The states of Alaska, Hawaii, and the District of Columbia are excluded from the models.

c. Controlling for the same set of variables of the model A in Table 8.1.

d. The estimates of Vehicle Fuel Economy of the model A in Table 8.1, the baseline specification model.

Moreover, in the mediation framework with the linear probability models, the magnitude of indirect effects can be estimated statistically through the Gelbach (2014) approach[56]. Table 8.4, abbreviated from Appendix D, delineates the test statistics in the

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[56] Gelbach, J. (2014), When Do Covariates Matter? And Which Ones, and How Much? Working manuscript.

Gelbach approach. As shown in the row of the *p*-value of the difference of coefficients between the reduced model and full model, pollutants statistically significantly reduced the magnitude of the coefficient of Vehicle Fuel Economy. For example, in the joint three pollutants full model (model 4), the coefficient of Vehicle Fuel Economy is -4.5×10^{-4} compared to -7.5×10^{-4} in the reduced model (model A). Thus, the pollutants jointly lower the coefficient by a magnitude of 3×10^{-4}. The estimated variance of the difference of the coefficients, as per Gelbach, is calculated by

$$\widehat{\sigma^2} = \widehat{\sigma_F^2} - \widehat{\sigma_R^2}\times\frac{{e_F}^2}{{e_R}^2}$$

The standard error is the square root of the estimated variance. The *t* statistic, dividing the difference of coefficients to the above standard error, is approximately equal to the *Z* statistics because the sample size is huge (3147864); hence, the *Z* statistic is used here for simplicity. The resulting Z statistic is -11.16. The *p*-value is very small (< 0.0001) indicating a highly statistical significance. In addition, the pollutants jointly account for about 40% indirect effect. [57] This is very close to the indirect effect found in the mediation framework with logistic regression models (39.7%).

Unfortunately, the statistical tests equivalent to the Gelbach approach are currently not available in either logistic regression models or probit regression models. Thus, I cannot conduct the similar tests in the mediation analyses in logistic regression models or probit regression models.

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[57] Calculated by $\frac{-0.00075-0.00045}{-0.00075}$= 40%

Table 8.4 Test of the Magnitude of Indirect Effects through Gelbach Approach in Mediation Analysis in Linear Probability Models [a,b,c], Abbreviated from Appendix D

Variable	A	1	1	3	4
Vehicle Fuel Economy (MPG)	-0.00075	-0.00054	-0.00064	-0.00064	-0.00045
	0.00007	0.00007	0.00007	0.00007	0.00007
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
$PM_{2.5}$		0.00040			0.00020
		0.00003			0.00003
		< 0.0001			< 0.0001
CO			0.00010		0.00045
			0.00008		0.00009
			0.19292#		< 0.0001
NO_2				0.00009	0.00004
				0.00001	0.00001
				< 0.0001	0.00030
Model Fit					
Root MSE	0.2807	0.2807	0.2812	0.2814	0.2820
Residual variance	0.0788	0.0788	0.0791	0.0792	0.0795
Gelbach Test Statistics					
Standard Error of coefficient of Vehicle Fuel Economy	6.547×10^{-5}	6.717×10^{-5}	6.685×10^{-5}	6.765×10^{-5}	7.107×10^{-5}
Error Square	4.287×10^{-9}	4.512×10^{-9}	4.469×10^{-9}	4.576×10^{-9}	5.050×10^{-9}
Est. Variance of Coeff Diff. [d] $\widehat{\sigma^2} = \widehat{\sigma_F^2} - \widehat{\sigma_R^2} \times \frac{e_F{}^2}{e_R{}^2}$		2.258×10^{-10}	1.657×10^{-10}	2.673×10^{-10}	7.228×10^{-10}
Coefficient of Vehicle Fuel Economy	-7.482×10^{-4}	-5.405×10^{-4}	-6.448×10^{-4}	-6.368×10^{-4}	-4.481×10^{-4}
Difference of Coeff. [d]		-2.077×10^{-4}	-1.034×10^{-4}	-1.114×10^{-4}	-3×10^{-4}
Z		-13.822	-8.032	-6.812	-11.160
p-value		<0.00001	<0.00001	<0.00001	<0.00001

Footnotes of the table

a. Modeling the outcome of Asthma (0 = No, 1=Yes) as continuous variable.

b. Model statistics are listed, per predictor, as estimated coefficient, standard error of the estimated coefficient, and *p*-value of the Wald's test statistics of the significance of coefficient, respectively. Estimates that are not statistically significant at the 5% level are marked with #

c. The states of Alaska, Hawaii, and the District of Columbia are excluded from the models.

d. Full model (with pollutants in covariates) – Reduced model (without pollutants in covariates).

N = 3147864 in all models here.

8.4 Assessing the Impact of Missing Data

As discussed in Chapter VII, the BRFSS data used in the dissertation have quite a large amount of missing data in income level (13.9%) and BMI (5%). There are missing data in race (1.1%) and education (0.31%), etc. The data collection process is independent of the dissertation hence I do not believe the missing data will systematically bias the estimation. Nevertheless, it is necessary to test the impact of missing data on the estimates of interest.

In the BRSS data, I create additional dummy indicator variables for income, BMI, and education, respectively, with 1 being missing, 0 otherwise. I then run the same logistic regression model as in section 8.1 on vehicle fuel economy, with and without controlling for the dummy variables, respectively, and all other variables. I also run the same logistic regression model as in section 8.1 without income, BMI, and education on a reduced dataset that excludes all records with missing values in any variables. The results are shown in Table 8.4.

Model X in Table 8.5 is to test the impact of missing income, BMI and Education. Model Y in Table 8.4 is the same model on the same dataset as X but without the dummy variables. As found in the estimates of the coefficients, missing income and BMI statistically significantly affects the prediction on asthma status. However, compare to Y, they do not have statistically significantly effects on the coefficient of vehicle fuel economy. As we see in the table, the estimated coefficient of vehicle fuel economy change from (X) -0.00542 to (Y) -0.00529, a roughly 2.4% change. The Wald's χ^2

difference between these two estimated coefficients is 2.23, it is not statistically significant (*p*-value = 0.5261 at 1 DF).

Model Z in the table is to test the impact of missing records. Model Z is on a reduced set of data that exclude any records that have missing value in any variables. Comparing Y to Z, the estimated coefficient of vehicle fuel economy change from (Y) -0.00529 to (Z) -0.00516, a roughly 2.46% change. The Wald's χ^2 difference between these two estimated coefficients is 8.0941, which is statistically significant (p-value = 0.0441 at 1 DF). However, the *p*-value is very close to 0.05, so the impact of the missing data is not severe. Moreover, the design of the survey, sampling process, and data collection process are carried out without my dissertation in mind, so there is no reason to believe the missing data will systematically bias my analysis.

Thus, I conclude that the missing data in BRFSS will not severely bias our estimation and inference.

Table 8.5 Test of the Impact of Missing Data [a]

Predictor [b]	**X**	**Y**	**Z**
Intercept	-2.47689	-2.48036	-2.51798
	0.01918	0.01917	0.02063
	< 0.0001	< 0.0001	< 0.0001
Vehicle Fuel Economy	-0.00542	-0.00529	-0.00516
(MPG)	0.00077	0.00077	0.00083
	< 0.0001	< 0.0001	< 0.0001
Missing Income information	-0.06414		
	0.00565		
	< 0.0001		
Missing Education Information	-0.05765		
	0.04090		
	0.15861#		
Missing BMI Information	0.01665		
	0.02227		
	0.45460#		
Fit statistics			
N	3647024	3647024	3147864
χ^2 of coefficient of MPG	49.28	47.05	38.9559
X *v*. Y Difference of χ^2	2.23		
p-value	0.5261		
Y *v*. Z Difference of χ^2		8.0941	
p-value		0.0441	

Footnotes of the table

a. Model statistics are listed as estimates, standard error of estimates, and p-value of the test statistics. Estimates that are not statistically significant at the 5% level are marked with #.

b. Other predictors are age, race, gender, smoking condition, diabetics, and heal coverage status. These are the same as the model 1 in Table 8-1 except for income, education, BMI, and year effects.

8.5 The Misspecification, Unobserved Variables, Sampling, and Other Problems

Our models could suffer misspecification problem in two ways: First, if I choose the wrong set of the covariates in the models of estimating the effects of vehicle fuel economy on asthma, and the model of estimating the effects of vehicle fuel economy on air pollutants. Second, if I miss the variables that correlate to the vehicle fuel economy and have effects on the asthma disproportionately. The first problem is unlikely true because these covariates are demographics (age, race, gender, etc.) and health related (BMI, diabetes, and healthcare coverage) variables that are much related to the health outcomes. In fact, each of the covariates have statistically significant coefficients in the models of vehicle fuel economy on asthma[58]. The second problem is the endogeneity problem. Among the unobserved variables, probably one of the most critical variable is the emission standards adoption by states over time. This is not documented in any of my data sources. However, the endogeneity problem can be alleviated by three possible solutions: 1. a proxy variables for the unobserved, 2. an instrumental variable, and 3. the panel data analysis. In the dissertation, I apply the first solution – using respondents' diabetic status, collected in BRFSS along with asthma, to proxy the unobserved variables which affects health and are correlated to the vehicle fuel economy other than the respondents' demographic characteristics; and by using the year fixed effects (that each year as a dummy variable versus the baseline year) to proxy the other time variant unobserved variables such as the emission standards adoption by states over time. The application of using these proxies will certainly alleviate the endogeneity. A better

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[58] Refer to Appendix C-1 for the estimated coefficients of the models

solution would be to find an instrumental variable (or instrumental variables) that are correlated to the vehicle fuel economy but not to asthma.

Another problem lies on pooling the BRFSS data from different years for the model estimations. Using the year fixed effects alleviates such a problem. In the models without controlling for year fixed effects, one makes a strong assumption that the effects of unobserved variables are temporally stagnant.

Table 8.6 presents the estimated coefficients of vehicle fuel economy in different models by year compared to the corresponding coefficients, and in the row of “All” pooling all years’ data together (year dummy variables are excluded). One can observe that there exist differential effects (largely different coefficients of vehicle fuel economy in different year) in different years. Meanwhile, the coefficient of vehicle fuel economy of ALL under No pollutants, which corresponds to the coefficient of vehicle fuel economy of baseline model A in Section 8.1, differs significantly to what is in Table 8.1 (-0.00957 vs -0.00556). The same pattern is found in mediation models (-0.00577 vs -0.00503). Thus, it is important to control for year fixed effects in the estimation.

Table 8.6 Estimated Coefficients of Vehicle Fuel Economy in Different Models [a] in Predicting Asthma

Year	Pollutants in the model (mediation)				
	No pollutants (baseline)	$PM_{2.5}$	CO	NO_2	All Pollutants
All	-0.00556	-0.00581	-0.00441	-0.00466	-0.00503
2001	-0.0063	-0.00205	0.000439	-0.00222	0.000505
2002	-0.00282	-0.00169	-0.00265	0.000241	0.000542
2003	-0.0133	-0.00638	-0.01216	-0.01002	-0.00221
2004	-0.01116	-0.00938	-0.01208	-0.00801	-0.00913
2005	-0.01751	-0.01674	-0.01923	-0.01578	-0.01939
2006	-0.0097	-0.00215	-0.00693	-0.00827	0.003978
2007	-0.00546	-0.00437	-0.0013	-0.01268	-0.00778
2008	-0.01577	-0.00983	-0.0128	-0.01327	-0.0076
2009	-0.00545	-0.00213	-0.00112	-0.0016	0.005972
2010	-0.006	-0.00603	-0.00577	-0.00335	-0.00341
2011	-0.00913	-0.00816	-0.0099	-0.00604	-0.0074

Footnote of the table

a. models correspond to model A in Table 8.1, models 1-4 in Table 8.3, respectively, without year dummy variables. Models are classified by year.

One of the other problems is the way that the annual average of the pollutant levels by state across time are derived. All of the $PM_{2.5}$, CO, and NO_2 raw data are provided in county level over time. They are averaged at the state year level and used in the models. First, this method treats every county the same; second, there are more counties in the later year however this will not be reflected on averaging; more importantly the earlier years' pollutants were collected in the monitors that were more likely put into the more polluted areas hence the earlier years' measurement in pollutants are artificially higher. Finding a good way to process the annual data accounting for such artifact is one of the future researches. A similar issue is in the variable asthma at the state year level. Moreover, averaging annual discards the seasonal variation of pollutants and asthma.

To assess the impact of different number of counties in different years, I construct a reduced air pollutant dataset (denoted as Balanced Panel, the non-reduced dataset denoted as Full Panel accordingly) that only contains records from the counties appearing in all years between 2001 ~ 2011. Table 8.7 below shows the difference in the number of counties between the Balanced Panel and Full Panel. We can see that there are between 120 ~ 200 counties not in all years indicating that additional counties are included to the pollutant data in different years.

Table 8.7 Number of Counties between the Balanced Panel and Full Panel

Year	Balanced Panel (Counties Appeared in All Years)	Full Panels (All counties)
2001	884	1099
2002	884	1098
2003	884	1097
2004	884	1077
2005	884	1063
2006	884	1022
2007	884	1014
2008	884	1002
2009	884	1005
2010	884	1021
2011	884	1049

To determine whether the additional pollutant data will bias the result, I inspect the following: 1. comparing the summary statistics between Balance Panel and Full Panel; 2. visual comparison of the summary data; 3. running the same mediation framework on the Balanced Panel. Table 8.8 lists the summary statistics of the pollutants in Balance Panel and Full Panel, respectively. The statistics are not largely different between the two panels, which implies that the additional counties over time should not be a problem. This can also be visualized in Figure 8.1. In fact, the relationships between pollutants and Vehicle Fuel Economy do not change when using Balanced Panel as shown in Table 8.9 with a stronger evidence of association than the Full Panel (the estimates of Vehicle Fuel Economy are all statistically significant at 10% level), and the model estimates of the same mediation framework on the Balanced Panel shown in Table 8.10 are similar to model estimates in corresponding Table 8.3.

Table 8.8 Summary Statistics of Air Pollutants between Balanced Panel and Full Panel

Variable	N	Mean	Std. Dev.	Min	Median	Max
Balanced Panel						
PM2.5 - the 98%ile of the daily average (PM1)	582	27.88	7.43	9	27.73	65.5
PM2.5 - the Weighted Annual Mean (PM2)	582	10.60	2.58	4.65	10.54	17.06
CO - the 2nd highest 1-hour measure (CO1)	562	4.42	4.03	0.4	3.51	45.05
CO - the 2nd highest non-overlapping 8-hr avg. (CO2)	562	2.59	2.22	0.3	2.2	26.35
NO2 - the 98%ile of the daily max 1-hr measure (NO)	543	47.49	18.47	10	44.75	182
Full Panel						
PM2.5 - the 98%ile of the daily average (PM1)	582	27.58	7.23	9	27.44	65.5
PM2.5 - the Weighted Annual Mean (PM2)	582	10.49	2.59	4.65	10.46	17.06
CO - the 2nd highest 1-hour measure (CO1)	564	4.39	4.03	0.2	3.5	45.05
CO - the 2nd highest non-overlapping 8-hr avg. (CO2)	564	2.57	2.22	0.3	2.2	26.35
NO2 - the 98%ile of the daily max 1-hr measure (NO)	543	46.49	18.81	10	44	182

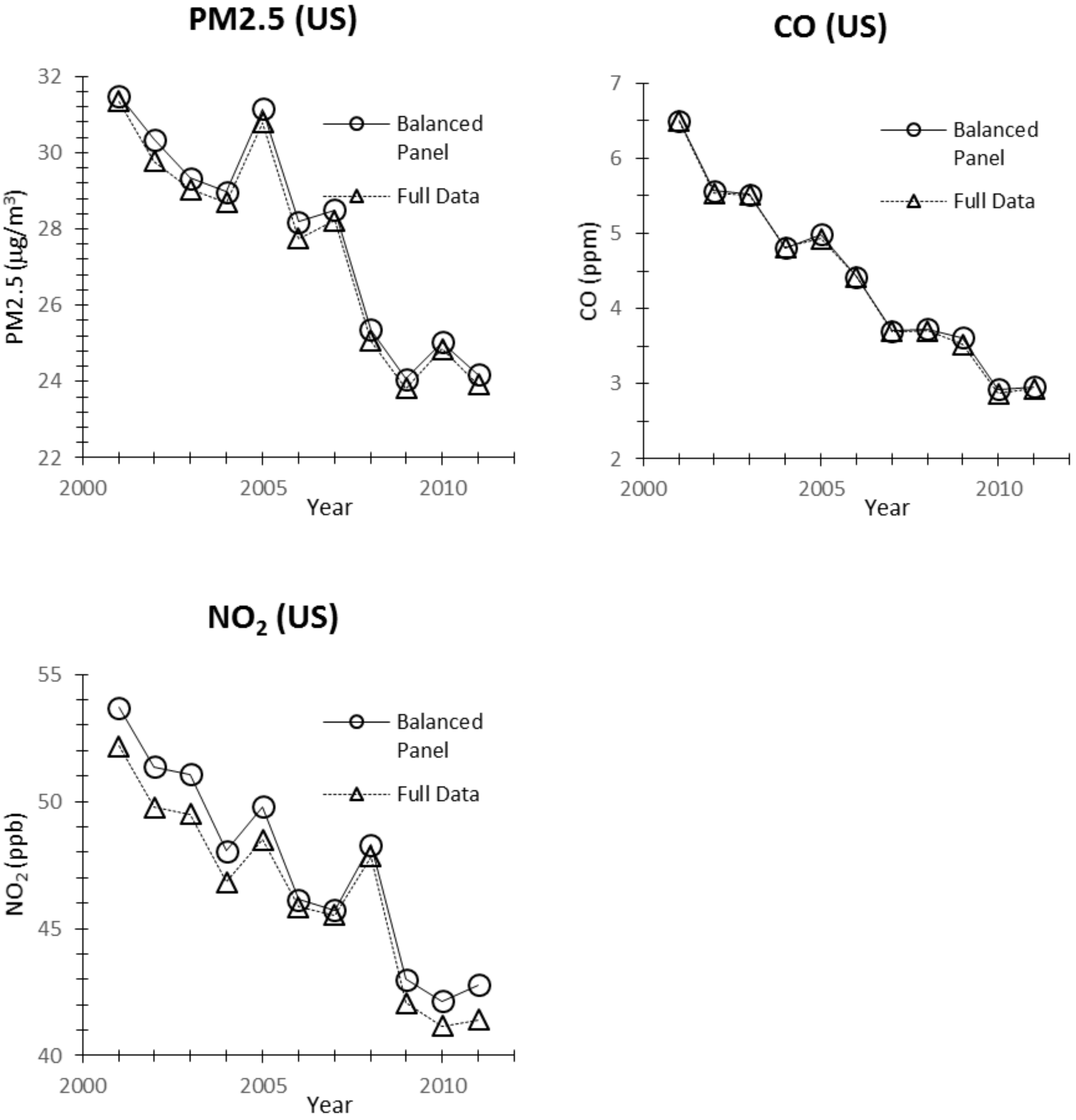

Figure 8.1 Air Pollutant Levels between Balanced Panel and Full Panel over Time

Table 8.9 Estimates [a,b,c] of Fixed Effects Model of Pollutants on Vehicle Fuel Economy Controlling for State Level Covariates, Balance Panel of Pollutant Data

*	Dependent Variable					
	$PM_{2.5}$		CO		NO_2	
Predictors						
Vehicle Fuel Economy (MPG)	-0.8412 0.2217 0.0002	-0.5509 0.2206 0.0129	-0.3030 0.0961 0.0017	-0.1800 0.0954 0.0598	-1.2843 0.5294 0.0157	-0.9828 0.5427 0.0709
GDP, per Capita ($)		-8.397×10^7 1.207×10^8 0.487		-1.383×10^8 55506891 0.0131		-1.17×10^8 2.91×10^8 0.6883
Population		-0.0373 0.0071 < 0.0001		-0.0133 0.0030 < 0.0001		-0.0429 0.0169 0.0117
Number of Vehicles (Millions)		0.0462 0.4690 0.9216		-0.0228 0.1969 0.9077		0.8685 1.1156 0.4367

Footnotes of the table

a. Modeling pollutants Particulate Matter ($PM_{2.5}$), Carbon Monoxide (CO), and Nitrogen Dioxide (NO_2), respectively.

b. Model estimates are listed as estimated coefficient, standard error of estimate, and *p*-value of the t-test statistics, respectively.

c. The states of Alaska, Hawaii, and the District of Columbia are excluded from the models.

Table 8.10 Logistic Regression Estimates [a,b] of Asthma on Fuel Economy and Pollutants, Controlling for Demographic and Health Variables [c] – Balanced Panel

Predictor	1	2	3	4	A[d]
Vehicle Fuel Economy (MPG)	-0.00709	-0.00840	-0.00822	-0.00604	-0.00957
	0.00086	0.00085	0.00086	0.00090	0.00084
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
$PM_{2.5}$	0.00510			0.00255	
	0.00036			0.00040	
	< 0.0001			< 0.0001	
CO		0.00109		0.00523	
		0.00094		0.00117	
		0.24735		< 0.0001	
NO_2			0.00110	0.00041	
			0.00013	0.00014	
			< 0.0001	0.00322	

Footnotes of the table

a. Model statistics are listed as estimated coefficient, standard error of the estimated coefficient, and *p*-value of the Wald's test statistics of the significance of coefficient, respectively. Estimates of the full set of covariates are presented in Appendix F.
b. The states of Alaska, Hawaii, and the District of Columbia are excluded from the models.
c. Controlling for the same set of variables of the model A in Table 8-1.
d. The estimates of Vehicle Fuel Economy of the model A in Table 8-1, the baseline specification model.

In addition, as discussed in section 7.1, the demographic characteristic summary of BRFSS data is not consistent to US population census data due to its purpose of data collection and sampling methods (details are not to discuss here). To assess whether our results are affected by the sampling methods, I conduct a sensitivity analysis on the same mediation framework as in sections 8.1, and 8.2 but weighted by the sample weight variable readily available in the BRFSS data. The estimation results are shown in Table 8.11. One can observe the consistent evidence in supporting my hypothesis such that a higher vehicle fuel economy decreases asthma prevalence (negative coefficient of vehicle fuel economy), and pollutants are mediators that transmit the effect of vehicle fuel economy on asthma (the coefficient of vehicle fuel economy is smaller when pollutant variables are added in the model), individually or jointly. Thus, the sampling method in BRFSS do not invalidate the empirical results I obtained in sections 8.1 and 8.3, respectively.

Interestingly, the indirect effect is much larger (~ 95.05% for the joint pollutants model – model 4 of Table 8.11)[59] in the weighted model than the non-weighted model (~ 39.7% for the joint pollutants model – model 4 of Table 8.4) in section 8.3. However, I notice the coefficients of CO are negative when it is individually or jointly included into the models. It implies a higher CO is associated with a lower asthma prevalence, which does not consistently support my hypothesis. Meanwhile, the effects of vehicle fuel economy on asthma is much smaller in the weighted model (coefficient of vehicle fuel economy is -0.00364 in model A of Table 8.11) than the non-weighted model (coefficient of vehicle fuel economy is -0.00957 in model A of Table 8.4).

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[59] Calculated by $\frac{-0.00364-0.00018}{-0.00364}$= 95.05%

Table 8.11 Logistic Regression Estimates [a,b] of Asthma on Fuel Economy and Pollutants, Controlling for Demographic and Health Variables [c] – Weighted by Sample

Predictor	1	2	3	4	A[d]
Vehicle Fuel Economy (MPG)	-0.00188 0.00004 < 0.0001	-0.00244 0.00004 < 0.0001	-0.00219 0.00004 < 0.0001	-0.00018 0.00004 < 0.0001	-0.00364 0.00004 < 0.0001
$PM_{2.5}$	0.00304 0.00001 < 0.0001			0.00183 0.00002 < 0.0001	
CO		-0.00211 0.00004 < 0.0001		-0.00096 0.00005 < 0.0001	
NO_2			0.00182 0.00001 < 0.0001	0.00149 0.00001 < 0.0001	

Footnotes of the table

a. Model statistics are listed as estimated coefficient, standard error of the estimated coefficient, and *p*-value of the Wald's test statistics of the significance of coefficient, respectively. Estimates that are not statistically significant at 5% level are marked with #. Estimates of the full set of covariates are presented in Appendix F.

b. The states of Alaska, Hawaii, and the District of Columbia are excluded from the models.

c. Controlling for the same set of variables of the model A in Table 8.1.

d. The estimates of Vehicle Fuel Economy of the model A in Table 8.1, the baseline specification model.

Finally, the spatial effects are ignored in the model estimation due to the availability of the data. First of all, one state's pollutants may be detected and counted partially by other states in the border areas; second, people may register vehicles in other states but largely travel in other states (for example live in one state but work in another). Because the spatial effects only pertain to the border area, they are relatively much smaller comparing to the vast areas of the state, they may not largely affect the estimation results even if they are considered.

8.6 Summary and Conclusions

The hypothesis of the dissertation is that a better vehicle fuel economy of the vehicle fleets on the roads has a better health outcome, a lower asthma rate, and such positive effect is through the improvement of the air quality measured in reduction of mobile source air pollutants.

The empirical analysis strategy is to utilize the mediation effects estimation framework. In this framework, air pollutants are mediators that transmit the effects of vehicle fuel economy to the health outcome asthma. As illustrated in Figure 8.2 (identical to Figure 5.1 in Chapter V)

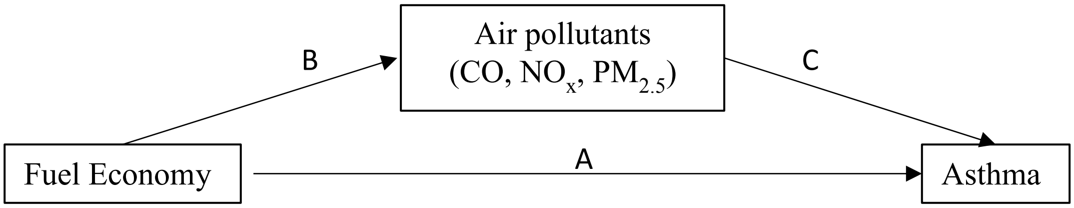

Figure 8.2 The Mediation Analysis Diagram for the Effect of Fuel Economy on Asthma through the Mechanism of Air Pollutants

The link between asthma and fuel economy (A) is the direct effect of fuel economy, the links among fuel economy, air pollutants and asthma (B / C) underlie the indirect effect. Based on Baron and Kenny (1986) the steps in estimating the pollutant mediated fuel economy effect on asthma are: (a) Regress asthma on fuel economy; (b) Regress air pollutants on fuel economy; (c) Regress asthma on air pollutants and fuel economy. All three regression models also control for other covariates. If all estimates in (a), (b), (c) are statistically significant, and the magnitude of the estimate from regression in (c) is smaller than the magnitude of the estimate from regression in (a) for fuel economy, such mediation (that fuel economy imposes effect on asthma via air pollutants) can be established.

In Table 8-1, the estimates of vehicle fuel economy in model A corresponds to (a), the coefficient is statistically significant at the 5% level and negative; this implies that a better vehicle fuel economy will have a lower asthma rate.

In Table 8.2, the estimates of vehicle fuel economy in models controlling for state level covariates correspond to (b), the coefficient of in $PM_{2.5}$ is statistically significant at the 5% level and negative; which implies that a lower $PM_{2.5}$ level in the air will lead to a lower asthma rate. The coefficients of CO and NO_2 are not statistically significant at the 5% level. However, the coefficients are both negative, it implying a weak evidence of effects.

In Table 8.3, the estimates of vehicle fuel economy in models 4 corresponds to (c), the coefficient is statistically significant at the 5% level and its magnitude is smaller than what is in (a) (0.00503 vs 0.00556). Thus, the mediation effects are established. However, because the coefficient is statistically significant at the 5% level in model 4, it implies such mediation effect is partial.

In a summary, I show the empirical evidence of the effects of vehicle fuel economy on asthma through the air pollutants mechanism, with limitations due to the data and the data processing scenarios with lack of control in spatial and seasonal variations.

CHAPTER IX

INTERPRETATION, POLICY IMPLICATIONS, AND FUTURE RESEARCH

This chapter interprets the empirical results and the policy implications to the fuel economy standards. Section 9.1 describe the Magnitude of Fuel Economy effects on Asthma; section 9.2 discuss the policy implications from the empirical analysis; section 9.3 suggests the direction of future research.

9.1 Magnitude of Fuel Economy Effects on Asthma from Empirical Analysis Results

Based on my empirical analysis model A in chapter VIII section 8.1, after controlling for individual subject's demographic and health status variables, the coefficient of vehicle fuel economy variable is -0.00957. This value implies the effect of 10 mpg improvement in fuel economy is associated with 0.0957 decrease of the odds of having asthma vs not having asthma in the logarithmic scale, or $e^{-0.0957} - 1 = -0.0913$, about a 9.13% decrease in such odds.

Based on my empirical analysis model 4 in chapter VIII section 8.3, after controlling for individual subject's demographic and health status variables through the three mobile source air pollutants ($PM_{2.5}$, CO, and NO_2) joint mechanism, the coefficient of vehicle fuel economy variable is -0.00577. This value implies the direct effect (after taking out the indirect effects of the joint $PM_{2.5}$, CO, and NO_2 mechanism) of 10 mpg improvement in fuel economy being associated with a 0.0577 decrease in the odds of asthma vs non-asthma in the logarithmic scale, or $e^{-0.0577}$- 1 = -0.0561, about 5.61% decrease in such odds beyond the joint $PM_{2.5}$, CO, and NO_2 mechanism (or the mediation pathway).

From the above two models, the indirect effect of which the joint $PM_{2.5}$, CO, and NO_2 mediation pathway accounts for (-0.00957 – (- 0.00577)) / (- 0.00957) = 0.3971, or 39.71%. Thus, 39.71% of the effects of vehicle fuel economy on asthma (in the measure of the odds of having asthma vs not having asthma in the logarithmic scale) are an indirect effect of the joint $PM_{2.5}$, CO, and NO_2 mediation pathway.

It’s concerning that only 39.71% -based on the model estimates- of the effects of vehicle fuel economy on asthma are transmitted by the indirect effect of the joint $PM_{2.5}$, CO, and NO_2 mediation pathway. There are three possible explanations: there are possibly 60.29% direct effects, other indirect effects transmitted by the other mediators, or significant measurement noise in the data used here. Because there is no scientific research proving vehicle fuel economy will cause asthma or logical justification relate them directly, it is unlikely there is any substantial direct effects. Automobiles emit many air pollutants that could cause asthma so other indirect effects seem plausible. In the sensitivity analysis conducted in section 8.5, the indirect effects are estimated as 95.05% when applying sample weights in the BRFSS data to the estimation framework. Thus, the sample weights largely “increase” the indirect effects. Therefore, significant measurement noise in the data is very likely the cause of the low indirect effects and other mediators may account for the rest. Exploring data noise and the other mediators and mediation pathways will be reserved for future research.

9.2 Policy Implications

The original purpose of CAFE standards, the vehicle fuel economy standards in the US, was to reduce oil consumption and dependency. The policy makers did not focus much on its health benefits. My dissertation aimed at assessing the impacts of fuel economy standards on health outcomes. Using asthma as the empirical analysis objectives, I showed empirical evidence of improving the vehicle economy reducing the probability (risk) in having asthma, thus, vehicle fuel economy standards provide health benefit in addition to preserving the oil resource. It gives additional arguments for policy marker to design and enforce stricter vehicle fuel economy standards.

CAFE standards were set primarily to reduce the oil consumption and dependency on oil import in response to the Oil Embargo in the 1970s. At the end of the 20th century and the first decade of the 21st century, CAFE standards are missioned as the means to control the vehicle carbon emission and alleviate the global warming. The standards have been tightened in the past few years since President Obama's Administration. My dissertation provides an additional argument, health benefits, for tightening the standards because the standards will increase the fuel economy of vehicle fleet.

9.3 Future Research

As described in Section 8.5, there are constraints from the source of data used in my empirical analysis and limitations in my model specifications. These constraints and limitations weaken the legitimacy of the evidence that vehicle fuel economy standards have positive effects on health through the air pollutants mechanism. Future studies on this topic thus will focus on making the data better suited for the empirical analysis, and will refine the model specifications taking the unobserved variables into account. For the data, I need to find better ways to aggregate the air pollutants into state-level so that the temporal difference of monitoring and between-county variation can be taken into account. Meanwhile, either exploring unobserved variables that are correlated to vehicle fuel economy and health, or an instrumental variable to account for the unobserved should be the greatest focal points. For the model specification, the baseline model and the mediation model can be modeled in the logistic fixed effects models, or can be modeled in instrumental variable methods should an instrument be found. In the former, determining a state level representative "person" is the key. The propensity scores method may be suitable in this purpose, which deserve further investigation. Nevertheless, the causal inference of vehicle fuel economy standards on health will be the focus.

My research can also be expanded to cost and benefit analyses on the vehicle fuel economy standards. Obviously, tightening the vehicle fuel economy standards require automobile manufacturer to research and apply costly new technologies; hence incurring additional cost. However, such cost may be outweighed by the health benefits alone since healthcare in the US is costly. Thus, reducing the health problems could bring large financial benefits to society as a whole. The health benefits add up to the benefits of reducing oil consumption, emissions, and dependency on foreign oil resources.

CHAPTER X

CONCLUSIONS

In this dissertation, I sought empirical evidence of the health effects of vehicle fuel economy standards, or CAFE standards, in the US. Using the data of vehicle registration, fuel sales, air pollutants, and health outcome (asthma), I applied the statistical mediation methods in the empirical analysis. Knowing the limitation of data and the limitation of the estimation framework, it is promising that I show empirical evidence of the link between fuel economy and asthma mediated by air pollutants pathway. Although the specification and model estimation suffers endogeneity problem that needs further refinement, the empirical results support the argument that an improving vehicle fuel economy is associated with the reduction of asthma, a disease is highly correlated to the air pollution, and such improvement is through the mechanism of reducing the air pollutants $PM_{2.5}$, CO and NO_2.

My dissertation contributes to the literature and knowledge to the research community in two aspects: first, the benefits of automobile fuel economy and an additional argument to tighten the automobile fuel economy standards; second, the application of the statistical mediation methods in econometric analysis. Future research will focus on the causal inference and expand to the cost benefit analysis on automobile fuel economy standards.

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APPENDIX A

HISTORICAL EVENTS

A.1 Key Events of California and US Vehicle Emissions Regulation[60]

Table A.1 Key Events of California and US Vehicle Emissions Regulation

Source: California Environmental Protection Agency, Air Resource Board (CARB)

United State Environmental Protection Agency (EPA)

Year	**Event**	**Reference**
Till 1930s	Industrialized air pollution were recognized among western countries and United States. However pollution of vehicle emissions were not well-aware	
1938	The first Sulfur Dioxide and Dust Fall Air Sampling stations (100 stations) of the US are set up in Pittsburgh PA under the Federal Works Progress Administration.	1
1940	First recognized episodes of smog occur in Los Angeles in the summer of 1943. Visibility is very low. People suffer from smarting eyes, respiratory discomfort, nausea, and vomiting. People blame a nearby butadiene plant. However, the situation does not improve when the plant is shut down. vehicles are found out to be the culprit a few years later	2

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[60] Contents of this appendix are compiled and modified from the California Environmental Protection Agency, Air Resource Board (CARB) (https://www.arb.ca.gov/html/brochure/history.htm) and The US Environmental Protection Agency (EPA) History of Reducing Air Pollution from Transportation in the United States (https://www.epa.gov/air-pollution-transportation/accomplishments-and-success-air-pollution-transportation), and the designated reference.

1943	The City of Los Angeles sets up the air pollution control program (APCP), and establishes the Bureau of Smoke Control in the Department of Health	
1946	The Los Angeles County Air Pollution Control District was established. It was the first of its kind in the nation	
June 10, 1947	California Governor Earl Warren signs into law the Air Pollution Control Act, authorizing the creation of an Air Pollution Control District in every county of the state	
1948	California passes Rule 50A, limiting smoke based upon the Ringelmann System	
	More than 100 electric transit systems were replaced with buses in 45 US cities (including Los Angeles)	
	Arie Haagen-Smit, a Caltech professor, discover the nature and causes of photochemical smog. He determines smog is formed from nitrogen oxides and hydrocarbons in the presence of ultraviolet radiation under the sun.	
1953	Los Angeles County started "Smoke School Program" for black smoke, beginning the standardization of "Visible Emission Programs" nationwide.	
	The Bureau of Air Sanitation was formed within the State Department of Public Health in California.	
	Los Angeles County Motor Vehicle Pollution Control laboratory began within the Los Angeles APCD.	
	The Bay Area Air Pollution Control District was established. It included the counties of Alameda, Contra Costa, Marin, Napa, San Francisco, San Mateo, Santa Clara, and portions of Solano and Sonoma counties.	
1955	US Federal Air Pollution Control Act of 1955 was enacted, providing for research and technical assistance and authorizing the Secretary of Health,	

	Education and Welfare to work towards a better understanding of the causes and effects of air pollution.	
1959	CA enacted legislation requiring the state Department of Public Health establish air quality standards and necessary controls for motor vehicle emissions. The first statewide air quality standards were set by the Department of Public Health for total suspended particulates, photochemical oxidants, sulfur dioxide, nitrogen dioxide, and carbon monoxide.	
	Federal Motor Vehicle Act of 1960 was enacted. Required federal research to address air pollution from motor vehicles.	
	The California Motor Vehicle Pollution Control Board was established. Primary function was to test and certify devices for installation on cars for sale in California.	
1961	The first automotive emissions control technology in the nation, Positive Crankcase Ventilation, was mandated by the California Motor Vehicle State Bureau of Air Sanitation to control hydrocarbon crankcase emissions.	
1963	First Federal Clean Air Act of 1963 was enacted. Empowered the Secretary of the federal Health, Education, and Welfare to define air quality criteria based on scientific studies. Provided grants to state and local air pollution control districts.	
1963	Positive Crankscase Ventilation requirement of 1961 went into effect on domestic passenger vehicles for sale in California.	
1964	Chrysler exhaust control system was approved by the California Motor Vehicle Pollution Control Board. Four other independent companies also received approvals.	

	Federal Clean Air Act of 1963 was amended by the Motor Vehicle Air Pollution Control Act of 1965. Direct regulation of air pollution by the federal government is provided for, and the Department of Health, Education, and Welfare was directed to establish auto emission standards.	
1966	Auto tailpipe emission standards for HC and CO were adopted by the California Motor Vehicle Pollution Control Board. First of their kind in the nation.	
	Federal Air Quality Act of 1967 was enacted. It established a framework for defining "air quality control regions" based on meteorological and topographical factors of air pollution. It allowed the State of California a waiver to set and enforce its own emissions standards for new vehicles based on California's unique need for more stringent controls.	
1967	The California Air Resources Board (CARB) was created from the merging of the California Motor Vehicle Pollution Control Board and the Bureau of Air Sanitation and its Laboratory. The Mulford-Carrell Air Resources Act was signed into law by, and Arie J. Haagen-Smit was appointed Chairman of the Air Resources Board by Governor Ronald Reagan	
1969	Air Quality Standards were set by CARB for total suspended particulates, photochemical oxidants, sulfur dioxide, nitrogen dioxide, and carbon monoxide.	
1970	Federal Clean Air Act Amendments of 1970 were enacted, serving served as the principal source of statutory authority for controlling air pollution, and establishing the basic US program for controlling air pollution.	
	National Environmental Policy Act (NEPA) was signed on Jan 1 1970 by President Nixon.	

	USEPA was created to protect all aspects of the environment on Dec. 2, 1970	3
	ARB adopted guidelines to control agricultural burning.	
	USEPA promulgated the National Ambient Air Quality Standards for particulates, photochemical oxidants (including ozone), hydrocarbons, carbon monoxide, nitrogen dioxide and sulfur dioxide.	
1971	CARB adopted the first automobile NOx standards in the nation.	
1973	OPEC oil embargo resulted in rising fuel cost, the use of smaller, more efficient automobiles, and more cost conservative use of fuel by industry and corresponding lower air emissions.	
	USEPA Working Group established to develop strategies for State Implementation Plan activities.	
	The California Air Pollution Control Officers Association was created.	
	The first two-way catalytic converters came into use as part of the ARB's Motor Vehicle Emission Control Program.	
1975	Volvo introduced 1977 year car billed as "Smog-Free". Featured the first three-way catalytic converter to control HC, NOx, and CO emissions.	
	CARB limited lead in gasoline.	
1976	The South Coast Air Quality Management District was formed. It included portions of Los Angeles, Orange, Riverside and San Bernardino counties.	
1977	Federal Clean Air Act Amendments of 1977 were enacted. Required the review of all National Ambient Air Quality Standards by 1980.	
1984	CA Smog Check Program went into effect identifying vehicles in need of maintenance and to assure the effectiveness of their emission control systems on a biennial basis	

1985	CARB adopted regulations effective on 1994 model cars requiring they be equipped with on-board computer systems to monitor emission performance and alert owners when there is a problem.	
1988	California Clean Air Act (CCAA) was signed by Governor Deukmejian. The Act set forth the framework for how air quality will be managed in California for the next 20 years.	
	The Clean Air Act Amendments of 1990 were signed into law by President George H.W. Bush. It required a number of new programs aimed at curbing urban ozone, rural acid rain, stratospheric ozone, toxic air pollutant emissions and vehicle emissions, and establishes a new, uniform national permit system.	
	CARB approved standards for cleaner burning gasoline and low and zero emission vehicles.	
1992	Phase I CA cleaning burning gasoline came to market. The result was 220 tons less of reactive organic gases (ROG) released every day (6 percent reduction), and elimination of the use of lead in gasoline. CARB required the addition of oxygenates in gasoline to cut carbon monoxide emissions by 10%.	
	CA fuel came to market.	
1993	ACRB enacted new standards for cleaner diesel fuel, resulting in a reduction of diesel particulate emissions by approximately 14 tons/day, 80 tons/day less SOx and 70 tons/day NOx emissions. Diesel busses and trucks are a major source of NOx emissions.	
	Smog Check II signed into law following lengthy negotiations with the USEPA, designed to meet the requirements of the Federal Clean Air Act as amended in 1990. This program targeted vehicles which pollute at least 2 to	

	25 times more than the average vehicle and requires repairs and retesting of offending vehicles.	
1994	US Court ordered USEPA to develop Federal Implementation Plan (FIP) for numerous non-attainment areas in CA.	
1996	CA's State Implementation Plan for ozone was approved by USEPA on September 26, 1996.	
	CA's Phase II Cleaner Burning Gasoline (CBG) came to market. CBG reduces lung-damaging ozone and ozone precursors by 300 tons/day, as well as reducing airborne toxic chemicals like benzene that can cause cancer. This is equivalent to taking 3.5 million cars off the road.	
	Big seven automakers commit to manufacture and sell Zero Emission Vehicles.	
	Marine engine regulations were adopted to greatly reduce smog-forming emissions and water pollution from outboard engines and personal watercraft.	
	CARB adopted LEVII emission standards for most mini vans, pickup trucks and sport utility vehicles up to 8,500 pounds gross vehicle weight to reduce emissions to passenger car levels by 2007.	
	CARB amended off-road engine regulations for lawn mowers, weed trimmers and other small engine power tools.	
1998	CARB identified diesel particulate emissions as a toxic air contaminant.	
	CARB approved a new set of gasoline rules that will ban the additive MTBE while preserving all the air-quality benefits obtained from the state's cleaner-burning gasoline program.	

	CARB adopted consumer products rules cut smog-forming emissions and volatile organic compounds from an estimated 2,500 common household products ranging from nail polish remover to glass cleaners.	
	CARB adopted a new regulation that reduces by over 70% the smog-forming emissions from portable gas cans.	
1999	The California Fuel Cell Partnership, a public-private venture to demonstrate fuel cell vehicles in CA, formally began. The Partnership includes auto manufactures, energy providers, fuel cell manufacturers and the State of California.	
	CARB adopted regulations to further reduce air pollution from transit buses operating in CA.	
	CARB amended the state's agricultural burning guidelines to reduce the public health impact of smoke from controlled burns.	
	CARB approved a comprehensive plan to reduce harmful particulate matter emissions from diesel powered equipment.	
2000	The CARB adopted new Environmental Justice Policies to ensure that residents of low-income and minority communities receive equal consideration under all ARB regulations and programs.	
	New standards were passed to reduce diesel soot and smog forming emissions by 90% from new large diesel engines. The new standards take effect with the 2007 model year and affect engines that power big rig trucks, trash trucks, delivery vans, and other large vehicles.	
2001	Zero-emission vehicle mandate was upheld, with modified requirements. Automakers were required to produce between 4,450 and 15,450 zero-emission cars starting in 2003.	
2002	CARB adopted an ATCM to reduce pollution from school bus idling.	

	CARB adopted new diesel fuel standards. The rule required greater than 95% reduction in the amount of sulfur in diesel fuel.	
	CARB adopted Heavy Duty Diesel Trucks idling controls. The regulation required Heavy Duty Diesel Trucks and interstate bus operators to shut their engines down after five minutes of non-essential idling. The regulation affected more than 400,000 trucks and buses registered in CA and all out-of-state trucks and buses operating in CA.	
	CARB adopted the nation's first "Greenhouse Gas" rule that requires automakers to begin selling vehicles with reduced greenhouse gas emissions by model year 2009	
2004	CARB adopted low sulfur diesel fuel rules for intrastate locomotives and harbor craft.	
	CARB signed a Memorandum of Understanding (MOU) with Union Pacific and Burlington Northern Santa Fe Railroads to significantly reduce diesel emissions in and around rail yards in CA.	
	CARB adopted regulation requiring engine manufacturers to install on-board diagnostic systems on HDDT engines beginning in 2010. Nitrogen oxide emissions will be reduced by 110 tons/day.	
	CARB adopted regulation limiting "unnecessary idling" of heavy diesel duty trucks (HDDT).	
2005	CARB implemented the Lower Emission School Bus Program to reduce children's exposure to both cancer-causing and smog forming pollution.	
	California switched to new ultra low sulfur diesel fuel.	
2006	AB 32 signed. The California Global Warming Solutions Act of 2006 establishes the first-in-the-world comprehensive program of regulatory and market mechanisms to achieve real, quantifiable, cost-effective reductions	

	in greenhouse gases (GHG). It makes the ARB responsible for monitoring and reducing GHG emissions.	
	Early action strategies are proposed to cut greenhouse gas emissions from the trucking industry, greener ports, cement and semiconductor industries, clean fuels and consumer products. Auto manufacturers must label vehicles to reflect smog and greenhouse gas emissions, helping consumers consider a vehicle's environmental impact.	
2007	CARB adopted greenhouse gas emissions limits to reflect 1990 levels, per the Global Warming Solutions Act of 2006 (AB32) -- a roughly 25 percent reduction by 2020.	
	CARB celebrates 40 years of clean-air success.	
	CARB offers rebates up to $5,000 to Californians who purchase or lease alternative fuel and electric vehicles.	
	The second E85 station opens to the public in Brentwood, funded in part by a $580,000 grant from CARB. Ethanol is a clean, renewable fuel that is a key component toward cleaner California air.	
	CARB adopts new Zero Emission Vehicle (ZEV) rules. The measure puts up to 65,000 cleaner vehicles on the road by 2012.	
	CARB receives an additional $48 million from AB 118 to comply with regulations aimed at cleaning up diesel emissions from an estimated 420,000 trucks and buses. These funds will help truckers pay for the engine retrofits, replacements, and other fuel efficient equipment.	
	New car label makes it easier to choose clean, efficient transportation. The Environmental Performance Label, on all new vehicles manufactured after Jan. 1, 2009, gives consumers a tool to compare climate change and smog forming emissions	

	CARB adopts a regulation requiring the use of lower sulfur content fuel which will eliminate 15 tons of diesel exhaust daily from ocean-going vessels. Both U.S. and foreign-flagged vessels are subject to the regulation which is the most stringent and comprehensive requirement for marine fuel-use in the world.	
2008	CARB adopts two critical regulations aimed at cleaning up harmful emissions from the estimated one million heavy-duty diesel trucks. One requires installation of diesel exhaust filters or engine replacement and the other requires installation of fuel efficient tires and aerodynamic devices.	
	CARB adopts a regulation on do-it-yourself cans of automobile refrigerant. The regulation includes a deposit and recycling program that will cost an estimated $11 for each ton of greenhouse gases prevented from entering the atmosphere.	
	CARB adopts regulations to control, and in some cases phase out, potent chemicals used in the manufacture of computer chips and other industries that contribute to global warming at many times greater than carbon dioxide.	
	CARB adopts the tire pressure regulation that requires California's automotive maintenance industry to check tire pressure of every vehicle they service. The regulation will annually eliminate 700,000 metric tons of greenhouse gas emissions, reduce the state's fuel consumption by 75 million gallons and extend the average tire's useful life by 4,700 miles.	
	CARB adopts the Low Carbon Fuel Standard aimed at diversifying fuels used for transportation which will achieve 16 million metric tons of greenhouse gas emission reductions by 2020. The regulation is described as	

	the most important early-actions called for under AB 32, the Global Warming Solutions Act.	
	CARB adopted amendments to the Pavley regulations that reduce greenhouse gas emissions in new passenger vehicles from 2009 through 2016.	
	CARB amends a landmark rule to reduce toxic emissions from the state's estimated 180,000 off-road vehicles such as tractors and bulldozers used in construction, mining and other industries. The amendments help business owners comply with the 2007 regulation.	
2009	CARB approves the cap-and-trade regulation, marking a significant milestone toward reducing California's greenhouse gas emissions under AB 32. The regulation helps drive the development of green jobs and set the state on track to a clean energy future.	
2010	CARB makes changes to diesel regulations that protect public health, provide relief and flexibility to California business owners of on-road and off-road equipment.	
	CARB offers funding assistance programs to truckers and buyers of on - and off-road clean vehicles. Business owners who took early action had a range of funding assistance options totaling hundreds of millions of dollars, and were able to tap into low-interest loans to operate clean vehicles.	
	Cleaner Fuels : CARB moves forward with the Low-Carbon Fuel Standard, to reduce the carbon intensity of existing fuels and develop even cleaner fuels, ultimately reducing the state's reliance on petroleum	
	National Program for Cleaner Cars:The Environmental Protection Agency, Department of Transportation and state of California align a single timeframe for corporate average fuel economy (CAFE) and greenhouse gas	

	standards for the next generation of cars and light-duty trucks for model years 2017-2025. The collaboration provides automakers with a single national program as they work to build the next generation of clean, fuel efficient cars.	
2011	Cap-and-Trade: ARB adopts cap-and-trade, a key element of the state's climate plan that will work with other climate programs to drive innovation and jobs, and promote efficiency and clean energy.	

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A.2 History of CAFE Standards[61]

Table A.2 History of CAFE Standards

Date	**Events**	**Region**
Oct. 1973 – Mar. 1974	The Organization of Arab Petroleum Exporting Countries (OAPEC) began oil embargo against US and other western countries. US Federal government imposes domestic price and allocation controls on petroleum, resulting in widespread shortages and gasoline lines, as well as rapid price increases.	World, US
1975	Congress enacts broad energy conservation bill ("EPCA"), including new auto fuel economy program. DOT is directed to set "corporate average fuel economy (CAFE)" standards for new cars starting in Model Year 1978, and for new light trucks starting in MY1979. The EPA is put in charge of measuring fuel economy for each model, laboratory test procedures, and the mileage window-stickers.	US
1976	Domestic automakers begin to introduce smaller models, new fuel-saving features (front-wheel-drive), and downsize existing models, to meet consumer demand and CAFE rules. Sales of small high-mpg import models grow.	US
1977	DOT issues CAFE standards for passenger cars, rising rapidly from 18.0 mpg in MY78 to 27.5 mpg in MY85 (the Congressional target).	US

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[61] Contents of this appendix are modified from CVC CAFE History (http://lobby.la.psu.edu/023_CAFE_Standards_1/Organizational_Statements/CVC/CVC_History.htm), the US DOT Corporate Average Fuel Economy (CAFE) Standards (https://www.transportation.gov/mission/sustainability/corporate-average-fuel-economy-cafe-standards), and the Pew Charitable Trusts History of Fuel Economy (http://www.pewtrusts.org/~/media/assets/2011/04/history-of-fuel-economy-clean-energy-factsheet.pdf)

Date	Events	Region
	DOT also establishes initial standards for light trucks, starting in MY79	
Oct. 1978	Second Arab oil embargo against U.S. New round of shortages and price increases, with Federal controls still in effect. US Congress passes "gas guzzler tax" (separate from CAFE program), administered by IRS, which assesses additional tax on passenger-car models with very low fuel-economy ratings.	World, US
1980	Congress amends CAFE law to allow longer time to use "credits" (for offset against shortfalls below the standard). DOT announces dramatic increases in future light truck CAFE standards, from 16.0 in MY80 mpg to 21.0 by MY85. DOT also threatens to impose further CAFE increases for cars (above 27.5 mpg) after MY85.	US
1981	Reagan Administration takes office and de-controls petroleum. That stimulates new exploration and production, eliminates gasoline shortages and stabilizes prices. DOT withdraws threat of post-MY85 CAFE increases for cars.	US
1980-1983	Consumer demand for new cars returns, and starts to shift back from smaller cars toward mid-size and larger vehicles. Automakers continue to downsize and improve fuel economy performance of new models, but sales of small high-mileage vehicles drop off.	US
1984	DOT adjusts light truck CAFE standards, in light of changes in consumer demand, to 19.5 mpg for MY85 and 20.0 mpg for MY86. Courts later uphold the adjustment	US
1985	DOT announces modest reduction in passenger car CAFE requirement (from 27.5 mpg to 26.0) for MY86-88, in light of	US

Date	Events	Region
	changed consumer demand, and to avoid job losses in U.S. auto industry. Most comments are favorable. Anti-car groups file suit, but courts later uphold the reduction. NHTSA issues new safety standards for cars and light trucks, which add to vehicle weight and reduce fuel economy.	
1987	Reagan Administration proposes repeal of CAFE law, cites it is harmful to U.S. jobs and competitiveness. Congress takes no action.	US
1988	Research study by Brookings Institution and Harvard Public Health School indicates substantial increase in highway traffic deaths has occurred, resulting from CAFE and downsizing. Congress passes new law to stimulate production of alternative-fuel and "dual-fuel" vehicles, by offering limited additional CAFE credits.	US
1989	Bush Administration takes office. DOT increases passenger car CAFE standard back to 27.5 mpg. Senate committee approves bill by Sen. Bryan to increase CAFE standards by 40% by 2001 (to 40 mpg for cars), over Bush Administration objections.	US
1990	Congress passes new Clean Air Act, with tighter tailpipe emissions standards for cars and light trucks, limiting opportunities for fuel-economy improvement. NHTSA issues comprehensive safety study, showing that downsizing of cars has increased death and injury risk for occupants, and warns against further downsizing and higher CAFE. Insurance Institute for Highway Safety (IIHS) releases its own study, with similar conclusions. Senate takes up Bryan bill to	US

Date	Events	Region
	raise CAFE. Bush Administration strongly objects, and Senate votes narrowly to table the bill	
1991	Amid oil price increase due to the Gulf War, Senate committee again approves Bryan bill to increase CAFE standards, and Bush Administration again objects. Senate also threatens to include CAFE provision in pending energy bill. CVC established, to represent vehicle consumers and other groups opposed to extreme CAFE legislation. HTSA repeats and updates its warning of increased safety risks from vehicle downsizing. CVC spearheads rallies of labor, business, farmers and others in cities around U.S., opposing CAFE increases. CVC also launches newspaper and TV ads, showing government crash test with large and small car, to warn about vehicle downsizing. Senate takes up energy bill, decides to drop controversial provisions on CAFE and oil drilling in Alaska.	US
1992	National Academy of Sciences (NAS) releases comprehensive study on auto fuel economy, confirming that CAFE program is "seriously flawed", and outlining the trade-offs of higher gas mileage (including cost, safety, utility, performance and pollution). Updated study from Harvard Injury Control Center again confirms adverse safety effects of CAFE and downsizing. Federal appeals court criticizes DOT for 1989 decision to increase MY90 car CAFE, without considering safety impact. House briefly considers bill to force reductions in carbon dioxide (CO2) emissions, which would lead to higher CAFE for motor vehicles, but then drops the proposal. U.S. participates in U.N. "Earth Summit" (Rio de Janeiro), pledges support for voluntary	US

Date	**Events**	**Region**
	efforts to moderate CO2 emissions. Congress passes energy bill, with no CAFE provisions. CAFE surfaces briefly as issue in Presidential campaign, with Bush opposed to increases, and Clinton first supporting an increase, but then modifying position to avoid taking actions that hurt U.S. auto workers.	
1993	Government and automakers launch new joint research program ("PNGV"), to develop new prototype mid-size car with fuel economy up to 80 mpg. White House releases "Climate Change Action Plan" on voluntary efforts to limit CO2 and other greenhouse gases, promises new advisory committee to consider CAFE and other vehicle-related efforts.	US
1994	DOT announces new threat to raise light-truck CAFE standards by 40% over next decade (1998-2006), from current level (20.7 mpg) to as high as 26-28 mpg, which threatens future availability of popular models and features. DOT cites concerns over climate change as primary reason. Light-truck users object strongly, send hundreds of letters against the proposal to DOT. White House appoints advisory committee on auto-related greenhouse gases ("Car Talks"), with majority of members already on record favoring large CAFE increases.	US
1995	Congress holds first hearing in 20 years on whether CAFE program may be counter-productive. CVC and other groups testify that program has outlived whatever usefulness it once had, and that higher	US

Date	Events	Region
	CAFE standards now threaten vehicle choice and highway safety. Legislation to "freeze" CAFE at current levels (27.5 mpg for cars, 20.7 for light trucks) introduced in House by Reps. Upton and Brown, with bi-partisan co-sponsors. Congress orders DOT not to impose any CAFE increases during Fiscal Year 1996, thus blocking any increase in MY98 light truck CAFE. White House advisory committee unable to reach consensus on final report, and disbands. Several anti-car members issue their own unofficial report, with predictable support for higher CAFE.	
1996	CAFE "freeze" legislation introduced in Senate, by Sens. Abraham and Levin, with bi-partisan co-sponsors. Senate considers bill to reduce gasoline tax, and two senators threaten to re-introduce bill for higher CAFE. Clinton Administration quietly reverses position on climate policy, decides to support binding reductions in CO2 by U.S. and other developed nations, as part of international agreement to be signed in December 1997.Congress again orders DOT not to increase CAFE during FY97, despite objections from Clinton Administration. That protects consumers from DOT increases in CAFE for MY99 light trucks.	US
1997	Permanent CAFE "freeze" bills re-introduced in House (H.R. 880) and Senate (S. 286), again with bi-partisan support. NHTSA releases updated safety studies, again confirming adverse safety effect of downsizing, for both cars and light trucks. Congress begins hearings on Administration climate policy, including energy restrictions and price increases, and economic impact of exemption for "developing"	US

Date	Events	Region
	countries. Resolution introduced by Senators Byrd and Hagel, with large bi-partisan support, urging President not to sign climate agreement which hurts the U.S. economy. Senate approves Byrd-Hagel resolution on climate treaty, 95-0. Congress again orders DOT not to increase CAFE during FY98, despite objections from Clinton Administration, to protect consumers from CAFE increases for MY2000 light trucks. U.S. negotiators attend climate conference in Kyoto, agree to proposed U.N. climate treaty which would require U.S. to make substantial cutbacks in energy use by 2010, but does not require any action by developing countries. Many in Congress object strongly, and White House announces it will delay submitting treaty for ratification.	
1998	Two new studies on effect of vehicle size and weight on highway safety by IIHS and Univ. of Michigan, based on analysis of real-world traffic data. Both studies confirm again that size and weight provide important safety benefits to occupants, in multi-vehicle as well as single-vehicle crashes. Those studies show relative safety advantage of light truck models, but anti-vehicle groups step up their attacks against trucks.Senate considers highway funding bill. Two senators plan amendment to impose large increase in light truck CAFE (from 20.7 to 27.5 mpg), with support from vehicle critics. Vehicle users object strongly. Sponsors decide to defer amendment for better opportunity. New White House study concedes that U.N. climate agreement would increase energy costs for American consumers, including electric bills and gasoline prices. Independent	US

Date	Events	Region
	economists believe the Administration study is overly optimistic, and that adverse effect would be considerably larger.Economic analysis by Energy Information Administration, part of U.S. Energy Department, shows severe adverse effects of Kyoto treaty on U.S. economy, far worse than White House projections. Congress again orders DOT not to increase CAFE during FY99, despite objections from Clinton Administration, to protect consumers from CAFE increases for MY2001 light trucks.	
1999	Permanent CAFE "freeze" bill re-introduced in the Senate (S. 147), again with bi-partisan support. Permanent CAFE "freeze" bill re-introduced in the House (H.R. 1992), also with bi-partisan support. Members of the Senate speak out on CAFE: 31 sign a letter supporting higher standards (despite the adverse effect on consumer choice), and 36 others sign a letter supporting extension of the freeze.The House Appropriations Committee approves a renewal of the freeze, as part of the DOT appropriations bill for FY2000 (H.R. 2084). The bill is then passed by the full House.An in-depth analysis by USA Today shows 46,000 lives lost to CAFE and downsizing since the late 1970's, confirming the findings of other highway safety researchers on the subject. By a vote of 55-40, the Senate rejects arguments from anti-vehicle activists and votes not to oppose the House-passed CAFE freeze extension, during debate on the Senate's DOT spending bill (S. 1143). House-Senate conferees then agree to include the freeze in the final DOT budget bill (H.R. 2084). On October 9, President Clinton signs the DOT budget for FY2000,	US

Date	Events	Region
	extending the CAFE freeze for another year. On October 20, environmental activist groups petition EPA to impose limits on auto emissions of CO2, the functional equivalent of higher CAFE, despite Congress' action in freezing CAFE. Four members of the House circulate a letter calling for higher CAFE, with support from pro-CAFE/anti-vehicle groups.	
2000	The House Appropriations Committee agrees to continue the CAFE freeze for another year. Pro-CAFE forces decide at last minute not to challenge the freeze on the House floor, turning their attention to the Senate instead.Three Senators try to block the CAFE freeze on the Senate floor, but other Senators speak up for consumer choice and safety. The two sides agree to continue the freeze for another year, and to ask for a new study of the issue by the National Academy of Sciences.The President signs the DOT appropriations bill, extending the CAFE freeze through FY2001 (thus preventing any CAFE increases thru MY2003).	
2001	Five senators and 10 House members introduce companion bills to force a drastic 30 percent increase in light-truck CAFE standards.	

APPENDIX B

CORRELATION OVER TIME BY STATES

B.1 Pearson Correlation Coefficients between Vehicle Fuel Economy and Air Pollutants over Time by State

Table B.1 Pearson Correlation Coefficients between Vehicle Fuel Economy and Air Pollutants over Time by State – Supplement to Table 7.9

State	**$PM_{2.5}$**		**NO_2**		**CO**	
	Pearson Correlation Coefficients	**p-value**	**Pearson Correlation Coefficients**	**p-value**	**Pearson Correlation Coefficients**	**p-value**
Alabama	-0.76686	< 0.0001	0.16964	< 0.0001	-0.52367	< 0.0001
Arizona	-0.51054	< 0.0001	0.612238	< 0.0001	-0.80381	< 0.0001
Arkansas	-0.14713	< 0.0001	-0.29218	< 0.0001	-0.58359	< 0.0001
California	-0.66331	< 0.0001	-0.73561	< 0.0001	-0.53211	< 0.0001
Colorado	0.146639	< 0.0001	0.021174	< 0.0001	-0.5901	< 0.0001
Connecticut	-0.25686	< 0.0001	-0.38872	< 0.0001	-0.52149	< 0.0001
Delaware	0.26422	< 0.0001	-0.07679	< 0.0001	0.432079	< 0.0001
D. Columbia	-0.84072	< 0.0001	-0.69838	< 0.0001	-0.33195	< 0.0001
Florida	-0.84375	< 0.0001	-0.43111	< 0.0001	-0.54735	< 0.0001
Georgia	-0.50734	< 0.0001	-0.61717	< 0.0001	-0.48793	< 0.0001
Idaho	0.334953	< 0.0001	-0.22484	< 0.0001	0.015225	< 0.0001
Illinois	-0.71784	< 0.0001	0.339169	< 0.0001	-0.88588	< 0.0001
Indiana	-0.62456	< 0.0001	-0.58807	< 0.0001	0.073545	< 0.0001
Iowa	-0.63578	< 0.0001	0.300506	< 0.0001	-0.38802	< 0.0001
Kansas	0.022375	< 0.0001	0.335448	< 0.0001	0.329206	< 0.0001
Kentucky	-0.4165	< 0.0001	-0.31292	< 0.0001	0.002304	0.5017
Louisiana	-0.53731	< 0.0001	-0.40617	< 0.0001	-0.17503	< 0.0001
Maine	-0.10306	< 0.0001	-0.04403	< 0.0001	0.276804	< 0.0001
Maryland	0.317288	< 0.0001	-0.01231	0.0004	0.126796	< 0.0001
Massachusetts	-0.67591	< 0.0001	-0.47481	< 0.0001	-0.5634	< 0.0001
Michigan	-0.16891	< 0.0001	-0.49446	< 0.0001	-0.36747	< 0.0001
Minnesota	-0.10362	< 0.0001	-0.07031	< 0.0001	-0.77967	< 0.0001
Mississippi	-0.08458	< 0.0001	0.33939	< 0.0001	-0.41435	< 0.0001

Missouri	-0.32008	< 0.0001	0.137321	< 0.0001	-0.2643	< 0.0001
Montana	-0.1931	< 0.0001	-0.24631	< 0.0001	-0.94644	< 0.0001
Nebraska	-0.32101	< 0.0001			-0.12998	< 0.0001
Nevada	-0.33742	< 0.0001	-0.4949	< 0.0001	-0.51718	< 0.0001
New Hampshire	-0.14377	< 0.0001	0.077023	< 0.0001	0.459158	< 0.0001
New Jersey	-0.60251	< 0.0001	-0.4567	< 0.0001	-0.56797	< 0.0001
New Mexico	-0.47613	< 0.0001	-0.48223	< 0.0001	-0.08424	< 0.0001
New York	-0.15033	< 0.0001	-0.05501	< 0.0001	-0.26239	< 0.0001
North Carolina	-0.36522	< 0.0001	-0.67483	< 0.0001	-0.64152	< 0.0001
North Dakota	0.024161	< 0.0001	0.109822	< 0.0001	-0.24038	< 0.0001
Ohio	-0.85425	< 0.0001	-0.88268	< 0.0001	-0.55078	< 0.0001
Oklahoma	-0.38265	< 0.0001	-0.42551	< 0.0001	-0.52803	< 0.0001
Oregon	0.242781	< 0.0001	0.192691	< 0.0001	0.563212	< 0.0001
Pennsylvania	-0.08219	< 0.0001	-0.15586	< 0.0001	-0.26248	< 0.0001
Rhode Island	-0.35929	< 0.0001	-0.42183	< 0.0001	-0.37905	< 0.0001
South Carolina	0.705474	< 0.0001	-0.7473	< 0.0001	0.711352	< 0.0001
South Dakota	-0.25008	< 0.0001	-0.40928	< 0.0001	0.959561	< 0.0001
Tennessee	0.566424	< 0.0001	-0.00449	0.320079	0.349456	< 0.0001
Texas	-0.12115	< 0.0001	0.32452	< 0.0001	0.269593	< 0.0001
Utah	-0.41208	< 0.0001	-0.6963	< 0.0001	-0.12443	< 0.0001
Vermont	0.428876	< 0.0001	0.080677	< 0.0001	0.838623	< 0.0001
Virginia	-0.86474	< 0.0001	-0.88136	< 0.0001	-0.76094	< 0.0001
Washington	0.200048	< 0.0001	0.189107	< 0.0001	-0.98785	< 0.0001
West Virginia	0.196919	< 0.0001	0.579269	< 0.0001	0.201061	< 0.0001
Wisconsin	0.678518	< 0.0001	0.211135	< 0.0001	0.321536	< 0.0001
Wyoming	-0.58431	< 0.0001	0.16533	< 0.0001	-0.28646	< 0.0001
Number of Correlation Coefficients<0	36		31		33	
Number of Correlation Coefficients>0	13		17		16	

APPENDIX C

LOGISTIC REGRESSION ESTIMATES

C.1 Logistic Regression Estimates of Asthma on Vehicle Fuel Economy, All Covariates

Table C.1a Logistic Regression Estimates of Asthma on Vehicle Fuel Economy [a,b,c,*] - Year Fixed Effects – Supplement to Table 8.1

Predictor	**A**	**B**	**C**	**D**	**E**
Intercept	-2.07196	-2.05171	-2.06995	-2.04420	-1.98748
	0.02261	0.02253	0.02400	0.02359	0.02247
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Vehicle Fuel Economy	-0.00957	-0.00931	-0.00932	-0.01016	-0.01007
(MPG)	0.00084	0.00084	0.00084	0.00084	0.00084
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Age	-0.00802	-0.00810	-0.00809	-0.00839	-0.00839
(year)	0.00013	0.00013	0.00013	0.00013	0.00013
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Caucasian	0.10136	0.09362	0.09332	0.09188	0.09255
(Yes/No)	0.00581	0.00580	0.00580	0.00579	0.00578
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Women	0.50810	0.50894	0.50872	0.50737	0.50798
(Yes/No)	0.00448	0.00447	0.00447	0.00447	0.00447
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
BMI	0.00753	0.00753	0.00753	0.00750	0.00751
	0.00012	0.00012	0.00012	0.00012	0.00012
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Has Health Plan	0.28478	0.28250	0.28232	0.29030	0.29010
(Yes/No)	0.00674	0.00673	0.00674	0.00671	0.00670
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Smoker	0.16036	0.16276	0.16252	0.15931	0.16133
(Yes/No)	0.00505	0.00504	0.00503	0.00503	0.00504
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Diabetic	0.43627	0.43946	0.43945	0.44078	0.44121
(Yes/No)	0.00600	0.00599	0.00599	0.00598	0.00598
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001

Income Level [d]					
10 - < 15k	-0.20740	-0.21483	-0.21519		
	0.00949	0.00948	0.00948		
	< 0.0001	< 0.0001	< 0.0001		
15 - < 20k	-0.39236	-0.40540	-0.40595		
	0.00925	0.00921	0.00922		
	< 0.0001	< 0.0001	< 0.0001		
20 - < 25k	-0.52325	-0.54138	-0.54222		
	0.00909	0.00901	0.00905		
	< 0.0001	< 0.0001	< 0.0001		
25 - < 35k	-0.66909	-0.68867	-0.68964		
	0.00891	0.00878	0.00886		
	< 0.0001	< 0.0001	< 0.0001		
35 - < 50k	-0.77444	-0.79274	-0.79367		
	0.00884	0.00866	0.00880		
	< 0.0001	< 0.0001	< 0.0001		
50 - < 75k	-0.83895	-0.85371	-0.85441		
	0.00908	0.00889	0.00905		
	< 0.0001	< 0.0001	< 0.0001		
>= 75k	-0.90888	-0.92009	-0.92020		
	0.00898	0.00880	0.00895		
	< 0.0001	< 0.0001	< 0.0001		
Income in Cardinal Categories [e] (1-8)				-0.12665	-0.12739
				0.00108	0.00105
				< 0.0001	< 0.0001
Below College vs College and Above Education		-0.00786			-0.03082
		0.00489			0.00482
		0.10801			< 0.0001
Education Level [f]					
No education	-0.16625				
	0.05819				
	0.00428				
Elementary School	0.03245				
	0.01204				
	0.00702				
Secondary School	0.15488				
	0.00863				
	< 0.0001				
High School	-0.09786				
	0.00573				
	< 0.0001				
Some College	0.04424				
	0.00550				
	< 0.0001				
Education in Cardinal Categories [g] (1-6)			0.00291	0.00732	
			0.00215	0.00214	
			0.17567	0.00063	
Year (vs 2011)					
2001	-0.15299	-0.15232	-0.15226	-0.15961	-0.15948
	0.00872	0.00872	0.00872	0.00871	0.00871
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
2002	-0.12191	-0.12187	-0.12182	-0.12807	-0.12796

	0.00799	0.00799	0.00799	0.00798	0.00798
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
2003	-0.09219	-0.09123	-0.09121	-0.09547	-0.09539
	0.00755	0.00755	0.00755	0.00755	0.00755
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
2004	-0.00941	-0.00901	-0.00897	-0.01191	-0.01196
	0.00684	0.00684	0.00684	0.00683	0.00683
	0.16860	0.18757	0.18937	0.08142	0.07995
2005	-0.01366	-0.01384	-0.01380	-0.01488	-0.01495
	0.00645	0.00644	0.00644	0.00644	0.00644
	0.03414	0.03179	0.03225	0.02092	0.02029
2006	0.02961	0.02966	0.02968	0.03121	0.03113
	0.00641	0.00641	0.00641	0.00641	0.00641
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
2007	0.01943	0.01929	0.01930	0.02131	0.02131
	0.00589	0.00589	0.00589	0.00589	0.00589
	0.00098	0.00106	0.00105	0.00030	0.00030
2008	0.08641	0.08593	0.08591	0.08987	0.08988
	0.00589	0.00588	0.00588	0.00588	0.00588
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
2009	0.05565	0.05540	0.05534	0.05974	0.05974
	0.00587	0.00587	0.00587	0.00587	0.00587
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
2010	0.11132	0.11094	0.11088	0.11580	0.11574
	0.00569	0.00568	0.00568	0.00568	0.00568
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001

Footnotes of the table:

a. Modeling the outcome of Asthma (Yes/No).

b. Model statistics are listed, per predictor, as estimated coefficient, standard error of the estimated coefficient, and *p*-value of the Wald’s test statistics of the significance of coefficient, respectively.

c. The states of Alaska, Hawaii, and District of Columbia are excluded from the models.

d. Base income level is ≤ $10,000. Unit is in chained (2005) US dollars.

e. Refer to Table 7-2 for the corresponding coding of income level.

f. Base education level is college and above.

g. Refer to Table 7-2 for the corresponding coding of education level.

*N = 3147864 in all models here.

Table C.1b Logistic Regression Estimates of Asthma on Vehicle Fuel Economy [a,b,c,*] - Year is Treated as Continuous

Predictor	A	B	C	D	E
Intercept	-2.22001	-2.19873	-2.21602	-2.19907	-2.14303
	0.02243	0.02234	0.02378	0.02333	0.02226
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Vehicle Fuel Economy	-0.00944	-0.00918	-0.00920	-0.01003	-0.00994
(MPG)	0.00083	0.00083	0.00083	0.00083	0.00083
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Age	-0.00798	-0.00806	-0.00805	-0.00834	-0.00835
(year)	0.00013	0.00013	0.00013	0.00013	0.00013
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Caucasian	0.10098	0.09321	0.09293	0.09146	0.09211
(Yes/No)	0.00581	0.00579	0.00580	0.00579	0.00578
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Women	0.50891	0.50973	0.50952	0.50821	0.50880
(Yes/No)	0.00448	0.00447	0.00447	0.00447	0.00447
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
BMI	0.00759	0.00759	0.00759	0.00756	0.00758
	0.00012	0.00012	0.00012	0.00012	0.00012
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Has Health Plan	0.28432	0.28200	0.28185	0.28984	0.28961
(Yes/No)	0.00674	0.00673	0.00673	0.00671	0.00670
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Smoker	0.16020	0.16260	0.16234	0.15912	0.16117
(Yes/No)	0.00505	0.00504	0.00503	0.00503	0.00503
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Diabetic	0.43609	0.43929	0.43927	0.44061	0.44105
(Yes/No)	0.00599	0.00599	0.00599	0.00598	0.00598
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Income Level [d]					
10 - < 15k	-0.20738	-0.21483	-0.21516		
	0.00949	0.00948	0.00948		
	< 0.0001	< 0.0001	< 0.0001		
15 - < 20k	-0.39250	-0.40560	-0.40611		
	0.00925	0.00921	0.00922		
	< 0.0001	< 0.0001	< 0.0001		
20 - < 25k	-0.52307	-0.54128	-0.54205		
	0.00909	0.00901	0.00905		
	< 0.0001	< 0.0001	< 0.0001		
25 - < 35k	-0.66890	-0.68860	-0.68948		
	0.00891	0.00877	0.00885		
	< 0.0001	< 0.0001	< 0.0001		
35 - < 50k	-0.77388	-0.79232	-0.79313		
	0.00884	0.00866	0.00880		
	< 0.0001	< 0.0001	< 0.0001		
50 - < 75k	-0.83773	-0.85264	-0.85319		
	0.00908	0.00889	0.00905		
	< 0.0001	< 0.0001	< 0.0001		

Predictor	**A**	**B**	**C**	**D**	**E**
>= 75k	-0.90732	-0.91868	-0.91862		
	0.00898	0.00879	0.00895		
	< 0.0001	< 0.0001	< 0.0001		
Income in Cardinal Categories[e] (1-8)				-0.12638	-0.12716
				0.00108	0.00105
				< 0.0001	< 0.0001
Below College vs College and Above Education		-0.00771			-0.03074
		0.00489			0.00482
		0.11491			< 0.0001
Education Level[f]					
No education	-0.16475				
	0.05819				
	0.00464				
Elementary School	0.03310				
	0.01204				
	0.00596				
Secondary School	0.15546				
	0.00863				
	< 0.0001				
High School	-0.09759				
	0.00573				
	< 0.0001				
Some College	0.04420				
	0.00550				
	< 0.0001				
Education in Cardinal Categories[g] (1-6)			0.00273	0.00714	
			0.00215	0.00214	
			0.20410	0.00085	
Year (- 2000)	0.02377	0.02364	0.02363	0.02493	0.02491
	0.00069	0.00069	0.00069	0.00069	0.00069
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001

Footnotes of the table

a. Modeling the outcome of Asthma (Yes/No).
b. Model statistics are listed, per predictor, as estimated coefficient, standard error of the estimated coefficient, and *p*-value of the Wald's test statistics of the significance of coefficient, respectively.
c. The states of Alaska, Hawaii, and District of Columbia are excluded from the models.
d. Base income level is ≤ $10,000. Unit is in chained (2005) US dollars.
e. Refer to Table 7-2 for the corresponding coding of income level.
f. Base education level is college and above.
g. Refer to Table 7-2 for the corresponding coding of education level.
*N = 3147864 in all models here.

Table C.1c Logistic Regression Estimates of Asthma on Vehicle Fuel Economy ^{a,b,c,*} - No Year Effects

Predictor	**A**	**B**	**B**	**D**	**E**
Intercept	-2.17275	-2.15360	-2.18060	-2.16860	-2.09997
	0.02237	0.02228	0.02374	0.02330	0.02221
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Vehicle Fuel Economy	-0.00556	-0.00531	-0.00533	-0.00754	-0.00592
(MPG)	0.00083	0.00083	0.00083	0.00013	0.00083
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Age	-0.00721	-0.00730	-0.00729	0.08444	-0.00755
(year)	0.00013	0.00013	0.00013	0.00578	0.00013
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Caucasian	0.09434	0.08699	0.08646	0.50937	0.08538
(Yes/No)	0.00581	0.00579	0.00580	0.00447	0.00578
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Women	0.50998	0.51101	0.51065	0.00747	0.51016
(Yes/No)	0.00448	0.00447	0.00447	0.00012	0.00447
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
BMI	0.00751	0.00749	0.00750	0.28231	0.00748
	0.00012	0.00012	0.00012	0.00670	0.00012
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Has Health Plan	0.27712	0.27517	0.27474	0.15642	0.28237
(Yes/No)	0.00674	0.00672	0.00673	0.00502	0.00669
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Smoker	0.15775	0.16007	0.16012	0.44987	0.15830
(Yes/No)	0.00505	0.00504	0.00503	0.00598	0.00503
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Diabetic	0.44478	0.44781	0.44791	-0.12427	0.45021
(Yes/No)	0.00599	0.00598	0.00598	0.00108	0.00598
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Income Level ^{d}					
10 - < 15k	-0.20807	-0.21507	-0.21564		
	0.00949	0.00947	0.00948		
	< 0.0001	< 0.0001	< 0.0001		
15 - < 20k	-0.39398	-0.40635	-0.40728		
	0.00924	0.00921	0.00922		
	< 0.0001	< 0.0001	< 0.0001		
20 - < 25k	-0.52323	-0.54027	-0.54179		
	0.00909	0.00901	0.00905		
	< 0.0001	< 0.0001	< 0.0001		
25 - < 35k	-0.67297	-0.69114	-0.69308		
	0.00890	0.00877	0.00885		
	< 0.0001	< 0.0001	< 0.0001		
35 - < 50k	-0.77465	-0.79131	-0.79353		
	0.00884	0.00866	0.00880		
	< 0.0001	< 0.0001	< 0.0001		
50 - < 75k	-0.83293	-0.84601	-0.84824		
	0.00907	0.00888	0.00905		
	< 0.0001	< 0.0001	< 0.0001		

Predictor	**A**	**B**	**B**	**D**	**E**
>= 75k	-0.89059	-0.90022	-0.90216		
	0.00896	0.00878	0.00893		
	< 0.0001	< 0.0001	< 0.0001		
Income in Cardinal Categories [e] (1-8)				0.00956	-0.12481
				0.00214	0.00105
				< 0.0001	< 0.0001
Below College vs College and Above Education		-0.00925			-0.03419
		0.00489			0.00481
		0.05845			< 0.0001
Education Level [f]					
No education	-0.17438				
	0.05817				
	0.00272				
Elementary School	0.02137				
	0.01203				
	0.07570				
Secondary School	0.14984				
	0.00863				
	< 0.0001				
High School	-0.09961				
	0.00573				
	< 0.0001				
Some College	0.04414				
	0.00549				
	< 0.0001				
Education in Cardinal Categories [g] (1-6)			0.00475	-0.00602	
			0.00215	0.00083	
			0.02675	< 0.0001	

Footnotes of the table

a. Modeling the outcome of Asthma (Yes/No).
b. Model statistics are listed, per predictor, as estimated coefficient, standard error of the estimated coefficient, and *p*-value of the Wald’s test statistics of the significance of coefficient, respectively.
c. The states of Alaska, Hawaii, and District of Columbia are excluded from the models.
d. Base income level is ≤ $10,000. Unit is in chained (2005) US dollars.
e. Refer to Table 7-2 for the corresponding coding of income level.
f. Base education level is college and above.
g. Refer to Table 7-2 for the corresponding coding of education level.
*N = 3147864 in all models here.

C.2 Logistic Regression Estimates of Asthma on Vehicle Fuel Economy and Pollutants, all Covariates.

Table C.2a Logistic Regression Estimates of Asthma on Vehicle Fuel Economy and Pollutants ^{a,b,c,*} - Supplement to Table 8.3

Predictor	1	2	3	4	A
Intercept	-2.27374	-2.10019	-2.16113	-2.27208	-2.07196
	0.02685	0.02306	0.02452	0.02885	0.02261
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Vehicle Fuel Economy (MPG)	-0.00699	-0.00825	-0.00816	-0.00577	-0.00957
	0.00086	0.00085	0.00086	0.00090	0.00084
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
PM2.5	0.00514			0.00258	
	0.00037			0.00041	
	< 0.0001			< 0.0001	
CO		0.00126		0.00552	
		0.00094		0.00117	
		0.18015		< 0.0001	
NO2			0.00114	0.00050	
			0.00013	0.00014	
			< 0.0001	0.00037	
Age (year)	-0.00798	-0.00814	-0.00800	-0.00804	-0.00802
	0.00013	0.00013	0.00014	0.00014	0.00013
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Caucasian (Yes/No)	0.10056	0.10030	0.10435	0.10457	0.10136
	0.00581	0.00590	0.00592	0.00592	0.00581
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Women (Yes/No)	0.50810	0.51208	0.51525	0.51452	0.50810
	0.00448	0.00454	0.00459	0.00459	0.00448
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
BMI	0.00753	0.00757	0.00758	0.00753	0.00753
	0.00012	0.00012	0.00013	0.00013	0.00012
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Has Health Plan (Yes/No)	0.28302	0.28934	0.28900	0.28951	0.28478
	0.00674	0.00684	0.00691	0.00691	0.00674
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Smoker (Yes/No)	0.16112	0.16071	0.15939	0.15953	0.16036
	0.00506	0.00512	0.00518	0.00518	0.00505
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Diabetic (Yes/No)	0.43579	0.43900	0.43285	0.43304	0.43627
	0.00600	0.00607	0.00617	0.00617	0.00600
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001

Predictor	**1**	**2**	**3**	**4**	**A**
Income Level ($) [d]					
10 - < 15k	-0.20704	-0.20771	-0.20909	-0.20905	-0.20740
	0.00949	0.00965	0.00977	0.00977	0.00949
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
15 - < 20k	-0.39149	-0.39117	-0.39039	-0.39022	-0.39236
	0.00925	0.00939	0.00951	0.00951	0.00925
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
20 - < 25k	-0.52279	-0.52412	-0.52134	-0.52142	-0.52325
	0.00909	0.00923	0.00934	0.00934	0.00909
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
25 - < 35k	-0.66866	-0.66911	-0.66586	-0.66594	-0.66909
	0.00891	0.00904	0.00915	0.00915	0.00891
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
35 - < 50k	-0.77414	-0.77474	-0.76799	-0.76831	-0.77444
	0.00884	0.00897	0.00907	0.00907	0.00884
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
50 - < 75k	-0.83932	-0.83819	-0.83185	-0.83266	-0.83895
	0.00908	0.00921	0.00930	0.00931	0.00908
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
>= 75k	-0.91009	-0.90982	-0.90471	-0.90566	-0.90888
	0.00898	0.00910	0.00919	0.00920	0.00898
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Education Level [e]					
No education	-0.16545	-0.18263	-0.16331	-0.16416	-0.16625
	0.05819	0.05877	0.05903	0.05903	0.05819
	0.00447	0.00189	0.00567	0.00542	0.00428
Elementary School	0.03264	0.02032	0.02854	0.02796	0.03245
	0.01204	0.01229	0.01237	0.01237	0.01204
	0.00669	0.09819	0.02101	0.02378	0.00702
Secondary School	0.15336	0.15271	0.15372	0.15318	0.15488
	0.00863	0.00875	0.00885	0.00885	0.00863
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
High School	-0.09919	-0.10009	-0.09727	-0.09753	-0.09786
	0.00573	0.00580	0.00587	0.00587	0.00573
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Some College	0.04379	0.04488	0.04419	0.04421	0.04424
	0.00550	0.00556	0.00561	0.00561	0.00550
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Year (vs 2011)					
2001	-0.17390	-0.15147	-0.16412	-0.17976	-0.15299
	0.00885	0.00908	0.00890	0.00945	0.00872
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
2002	-0.13459	-0.12147	-0.13185	-0.14111	-0.12191
	0.00805	0.00819	0.00815	0.00841	0.00799
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
2003	-0.09796	-0.09335	-0.09963	-0.10666	-0.09219
	0.00757	0.00771	0.00763	0.00783	0.00755
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
2004	-0.01348	-0.00973	-0.01032	-0.01607	-0.00941
	0.00685	0.00695	0.00693	0.00708	0.00684

Predictor	**1**	**2**	**3**	**4**	**A**
	0.04900	0.16160	0.13663	0.02329	0.16860
2005	-0.03448	-0.01442	-0.01865	-0.03258	-0.01366
	0.00662	0.00655	0.00653	0.00686	0.00645
	< 0.0001	0.02780	0.00427	< 0.0001	0.03414
2006	0.02755	0.03388	0.02802	0.03185	0.02961
	0.00642	0.00656	0.00656	0.00672	0.00641
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
2007	0.01528	0.02232	0.02334	0.02542	0.01943
	0.00590	0.00604	0.00606	0.00626	0.00589
	0.00962	0.00022	0.00012	< 0.0001	0.00098
2008	0.09945	0.08901	0.08298	0.10163	0.08641
	0.00596	0.00602	0.00615	0.00644	0.00589
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
2009	0.07566	0.05510	0.06564	0.07696	0.05565
	0.00605	0.00602	0.00608	0.00641	0.00587
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
2010	0.12967	0.10694	0.12198	0.13018	0.11132
	0.00584	0.00585	0.00589	0.00622	0.00569
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001

Footnotes of the table

a. Modeling the outcome of Asthma (Yes/No).

b. Model statistics are listed, per predictor, as estimated coefficient, standard error of the estimated coefficient, and *p*-value of the Wald's test statistics of the significance of coefficient, respectively.

c. The states of Alaska, Hawaii, and District of Columbia are excluded from the models.

d. Base income level is ≤ $10,000. Unit is in chained (2005) US dollars.

e. Base education level is college and above.

*N = 3147864 in all models here.

Table C.2b Logistic Regression Estimates [a,b] of Asthma on Fuel Economy and Pollutants, Controlling for Demographic and Health Variables [c] – Year is Treated as Continuous – Interest Covariates Only

Predictor	**1**	**2**	**3**	**4**	**A[d]**
Vehicle Fuel Economy (MPG)	-0.00703 0.00085 < 0.0001	-0.00810 0.00085 < 0.0001	-0.00803 0.00086 < 0.0001	-0.00574 0.00090 < 0.0001	-0.00944 0.00083 < 0.0001
$PM_{2.5}$	0.00485 0.00036 < 0.0001			0.00233 0.00039 < 0.0001	
CO		0.00090 0.00094 0.33550		0.00470 0.00116 < 0.0001	
NO_2			0.00125 0.00013 < 0.0001	0.00069 0.00014 < 0.0001	

Footnotes of the table

a. Model statistics are listed as estimated coefficient, standard error of the estimated coefficient, and p-value of the Wald's test statistics of the significance of coefficient, respectively. Estimates of the full set of covariates are presented in Appendix A-5.

b. The states of Alaska, Hawaii, and District of Columbia are excluded from the models.

c. Controlling for the same set of variables of the model A in Table 8-1.

d. The estimates of Vehicle Fuel Economy of the model A in Table 8-1, the baseline specification model.

Table C.2c Logistic Regression Estimates [a,b] of Asthma on Fuel Economy and Pollutants, Controlling for Demographic and Health Variables [c] – No Year Effects

Predictor	**1**	**2**	**3**	**4**	**A[d]**
Vehicle Fuel Economy	-0.00581	-0.00441	-0.00466	-0.00503	-0.00556
(MPG)	0.00085	0.00084	0.00085	0.00089	0.00083
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
$PM_{2.5}$	-0.00039			-0.00170	
	0.00033			0.00038	
	0.23452			< 0.0001	
CO		-0.01089		-0.01050	
		0.00089		0.00111	
		< 0.0001		< 0.0001	
NO_2			0.00047	0.00033	
			0.00013	0.00014	
			0.00023	0.01516	

Footnotes of the table

a. Model statistics are listed as estimated coefficient, standard error of the estimated coefficient, and p-value of the Wald’s test statistics of the significance of coefficient, respectively. Estimates of the full set of covariates are presented in Appendix A-5.

b. The states of Alaska, Hawaii, and District of Columbia are excluded from the models.

c. Controlling for the same set of variables of the model A in Table 8-1.

d. The estimates of Vehicle Fuel Economy of the model A in Table 8-1, the baseline specification model.

APPENDIX D

LINEAR PROBABILITY MODEL ESTIMATES

D.1 Mediation Estimation in Linear Probability Model

Table D.1 Linear Regression Estimates of Asthma on Vehicle Fuel Economy ^{a,b,c,*} - Year Fixed Effects, and Gelbach Test

Predictors	A	1	2	3	4
Intercept	0.13268	0.11837	0.13027	0.12669	0.11880
	0.00191	0.00218	0.00195	0.00206	0.00234
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Vehicle Fuel Economy	-0.00075	-0.00054	-0.00064	-0.00064	-0.00045
(MPG)	0.00007	0.00007	0.00007	0.00007	0.00007
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
$PM_{2.5}$		0.00040			0.00020
		0.00003			0.00003
		< 0.0001			< 0.0001
CO			0.00010		0.00045
			0.00008		0.00009
			0.19292		< 0.0001
NO_2				0.00009	0.00004
				0.00001	0.00001
				< 0.0001	0.00030
Age	-0.00065	-0.00064	-0.00066	-0.00065	-0.00066
(year)	0.00001	0.00001	0.00001	0.00001	0.00001
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Caucasian	0.00835	0.00833	0.00830	0.00870	0.00847
(Yes/No)	0.00047	0.00047	0.00048	0.00048	0.00049
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Women	0.03729	0.03729	0.03772	0.03793	0.03844
(Yes/No)	0.00033	0.00033	0.00033	0.00034	0.00034
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
BMI	0.00080	0.00080	0.00081	0.00080	0.00081
	0.00001	0.00001	0.00001	0.00001	0.00001
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Has Health Plan	0.02423	0.02410	0.02470	0.02471	0.02516
(Yes/No)	0.00053	0.00053	0.00054	0.00055	0.00056
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Smoker	0.01383	0.01389	0.01393	0.01382	0.01398
(Yes/No)	0.00042	0.00042	0.00043	0.00043	0.00044
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001

Diabetic (Yes/No)	0.04052	0.04048	0.04090	0.04037	0.04078
	0.00054	0.00054	0.00055	0.00056	0.00057
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Income Level ($) [d]					
10 - < 15k	-0.02814	-0.02811	-0.02827	-0.02830	-0.02843
	0.00094	0.00094	0.00096	0.00097	0.00099
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
15 - < 20k	-0.04805	-0.04799	-0.04811	-0.04786	-0.04788
	0.00088	0.00088	0.00090	0.00091	0.00093
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
20 - < 25k	-0.06013	-0.06009	-0.06044	-0.06001	-0.06031
	0.00085	0.00085	0.00087	0.00088	0.00090
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
25 - < 35k	-0.07204	-0.07200	-0.07234	-0.07188	-0.07217
	0.00083	0.00083	0.00084	0.00085	0.00087
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
35 - < 50k	-0.07999	-0.07996	-0.08036	-0.07968	-0.08003
	0.00082	0.00082	0.00083	0.00084	0.00086
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
50 - < 75k	-0.08477	-0.08479	-0.08510	-0.08449	-0.08480
	0.00083	0.00083	0.00084	0.00085	0.00087
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
>= 75k	-0.08926	-0.08935	-0.08973	-0.08927	-0.08968
	0.00082	0.00082	0.00084	0.00085	0.00086
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Education Level [e]					
No education	-0.01626	-0.01618	-0.01774	-0.01612	-0.01748
	0.00474	0.00474	0.00478	0.00485	0.00489
	0.00060	0.00065	0.00021	0.00089	0.00035
Elementary School	0.00182	0.00187	0.00068	0.00142	0.00019
	0.00104	0.00104	0.00106	0.00107	0.00110
	0.07981	0.07180	0.52417	0.18475	0.86406
Secondary School	0.01558	0.01547	0.01544	0.01544	0.01527
	0.00075	0.00075	0.00076	0.00077	0.00079
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
High School	-0.00824	-0.00832	-0.00846	-0.00825	-0.00854
	0.00044	0.00044	0.00044	0.00045	0.00046
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Some College	0.00328	0.00326	0.00335	0.00330	0.00332
	0.00042	0.00042	0.00043	0.00044	0.00044
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Year (vs 2011)					
2001	-0.01844	-0.02150	-0.01806	-0.02059	-0.02249
	0.00084	0.00087	0.00089	0.00087	0.00096
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
2002	-0.01613	-0.01855	-0.01579	-0.01817	-0.01953
	0.00079	0.00081	0.00083	0.00082	0.00088
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
2003	-0.01395	-0.01585	-0.01372	-0.01582	-0.01699
	0.00077	0.00078	0.00080	0.00079	0.00084
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001

2004	-0.00758	-0.00934	-0.00726	-0.00891	-0.00994
	0.00073	0.00074	0.00075	0.00075	0.00079
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
2005	-0.00796	-0.01101	-0.00768	-0.00961	-0.01128
	0.00070	0.00073	0.00072	0.00072	0.00078
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
2006	-0.00456	-0.00616	-0.00385	-0.00591	-0.00617
	0.00070	0.00071	0.00072	0.00072	0.00075
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
2007	-0.00535	-0.00713	-0.00476	-0.00628	-0.00669
	0.00066	0.00067	0.00067	0.00069	0.00071
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
2008	0.00001	-0.00045	0.00060	-0.00145	-0.00053
	0.00066	0.00067	0.00067	0.00071	0.00072
	0.98612	0.50178	0.37316	0.04015	0.45815
2009	-0.00247	-0.00240	-0.00215	-0.00289	-0.00259
	0.00066	0.00066	0.00067	0.00069	0.00069
	0.00017	0.00026	0.00120	< 0.0001	0.00019
2010	0.00209	0.00203	0.00209	0.00178	0.00181
	0.00065	0.00065	0.00065	0.00068	0.00068
	0.00139	0.00191	0.00141	0.00906	0.00792
Model Fit					
Root MSE	0.2807	0.2807	0.2812	0.2814	0.2820
Residual variance	0.0788	0.0788	0.0791	0.0792	0.0795
Gelbach Test					
Standard Error of coefficient of Vehicle Fuel Economy	6.547×10^{-5}	6.717×10^{-5}	6.685×10^{-5}	6.765×10^{-5}	7.107×10^{-5}
Error Square	4.287×10^{-9}	4.512×10^{-9}	4.469×10^{-9}	4.576×10^{-9}	5.050×10^{-9}
Est. Variance of Coeff Diff. [f] $\widehat{\sigma^2} = \widehat{\sigma_F^2} - \widehat{\sigma_R^2}\times\frac{{e_F}^2}{{e_R}^2}$		2.258×10^{-10}	1.657×10^{-10}	2.673×10^{-10}	7.228×10^{-10}
Coefficient of Vehicle Fuel Economy	-7.482×10^{-4}	-5.405×10^{-4}	-6.448×10^{-4}	-6.368×10^{-4}	-4.481×10^{-4}
Difference of Coeff. [f]		-2.077×10^{-4}	-1.034×10^{-4}	-1.114×10^{-4}	-3×10^{-4}
Z		-13.822	-8.032	-6.812	-11.160
p-value		<0.00001	<0.00001	<0.00001	<0.00001

Footnotes of the table

a. Modeling the outcome of Asthma (0 = No, 1=Yes) as continuous variable.

b. Model statistics are listed, per predictor, as estimated coefficient, standard error of the estimated coefficient, and *p*-value of the Wald's test statistics of the significance of coefficient, respectively.

c. The states of Alaska, Hawaii, and District of Columbia are excluded from the models.

d. Base income level is ≤ $10,000. Unit is in chained (2005) US dollars.

e. Base education level is college and above.

f. Full model – Reduced model.

*N = 3147864 in all models here.

APPENDIX E

PROBIT REGRESSION MODEL ESTIMATES

E.1 Mediation Estimation in Probit Models

Table E.1 Probit Regression Estimates of Asthma on Vehicle Fuel Economy [a,b,c,*] - Year Fixed Effects

Predictors	A	1	2	3	4
Intercept	0.08435	0.08435	0.08964	0.08533	0.09402
	0.00197	0.00207	0.00203	0.00205	0.00223
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Vehicle Fuel Economy	-0.00466	-0.00336	-0.00397	-0.00393	-0.00271
(MPG)	0.00042	0.00043	0.00043	0.00043	0.00045
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
$PM_{2.5}$		0.00254			0.00127
		0.00019			0.00021
		< 0.0001			< 0.0001
CO			0.00073		0.00301
			0.00048		0.00059
			0.12587		< 0.0001
NO_2				0.00058	0.00026
				0.00007	0.00007
				< 0.0001	0.00031
Age	-0.00399	-0.00397	-0.00405	-0.00400	-0.00406
(year)	0.00007	0.00007	0.00007	0.00007	0.00007
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Caucasian	0.05082	0.05058	0.05040	0.05270	0.05117
(Yes/No)	0.00298	0.00298	0.00302	0.00303	0.00308
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Women	0.25049	0.25047	0.25257	0.25381	0.25630
(Yes/No)	0.00219	0.00219	0.00222	0.00225	0.00228
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
BMI	0.00417	0.00417	0.00420	0.00417	0.00420
	0.00007	0.00007	0.00007	0.00007	0.00007
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Has Health Plan	0.14133	0.14049	0.14371	0.14385	0.14609
(Yes/No)	0.00342	0.00342	0.00347	0.00350	0.00356
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Smoker	0.07642	0.07677	0.07672	0.07601	0.07671
(Yes/No)	0.00260	0.00260	0.00264	0.00267	0.00271
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001

Diabetic	0.22075	0.22049	0.22228	0.21923	0.22087
(Yes/No)	0.00317	0.00317	0.00322	0.00327	0.00332
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Income Level ($) [d]					
10 - < 15k	-0.11418	-0.11401	-0.11438	-0.11503	-0.11516
	0.00518	0.00518	0.00527	0.00533	0.00543
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
15 - < 20k	-0.21262	-0.21222	-0.21216	-0.21161	-0.21086
	0.00499	0.00499	0.00507	0.00513	0.00522
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
20 - < 25k	-0.27972	-0.27954	-0.28044	-0.27891	-0.27951
	0.00487	0.00487	0.00495	0.00500	0.00509
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
25 - < 35k	-0.35302	-0.35286	-0.35331	-0.35164	-0.35181
	0.00474	0.00474	0.00482	0.00487	0.00495
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
35 - < 50k	-0.40552	-0.40542	-0.40603	-0.40272	-0.40299
	0.00469	0.00469	0.00477	0.00482	0.00490
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
50 - < 75k	-0.43740	-0.43762	-0.43740	-0.43461	-0.43428
	0.00480	0.00480	0.00487	0.00492	0.00500
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
>= 75k	-0.47088	-0.47155	-0.47175	-0.46966	-0.47000
	0.00475	0.00475	0.00482	0.00487	0.00494
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Education Level [e]					
No education	-0.08732	-0.08686	-0.09565	-0.08658	-0.09417
	0.02985	0.02985	0.03010	0.03034	0.03061
	0.00344	0.00361	0.00149	0.00432	0.00210
Elementary School	0.01721	0.01739	0.01083	0.01509	0.00825
	0.00628	0.00628	0.00641	0.00645	0.00660
	0.00612	0.00563	0.09139	0.01943	0.21109
Secondary School	0.08191	0.08116	0.08081	0.08108	0.07979
	0.00451	0.00451	0.00457	0.00463	0.00469
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
High School	-0.05016	-0.05081	-0.05139	-0.05004	-0.05164
	0.00286	0.00286	0.00290	0.00293	0.00297
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Some College	0.02144	0.02120	0.02172	0.02149	0.02144
	0.00275	0.00276	0.00279	0.00282	0.00286
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Year (vs 2011)					
2001	-0.07523	-0.08557	-0.07472	-0.08087	-0.08904
	0.00433	0.00440	0.00452	0.00442	0.00471
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
2002	-0.05965	-0.06590	-0.05964	-0.06474	-0.06965
	0.00398	0.00401	0.00409	0.00406	0.00420
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
2003	-0.04513	-0.04796	-0.04590	-0.04899	-0.05282
	0.00378	0.00379	0.00386	0.00382	0.00392
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
2004	-0.00423	-0.00621	-0.00450	-0.00478	-0.00783

	0.00346	0.00346	0.00352	0.00351	0.00359
	0.22147	0.07259	0.20119	0.17307	0.02906
2005	-0.00712	-0.01730	-0.00764	-0.00974	-0.01679
	0.00325	0.00334	0.00331	0.00329	0.00346
	0.02842	< 0.0001	0.02094	0.00310	< 0.0001
2006	0.01410	0.01311	0.01621	0.01336	0.01528
	0.00325	0.00325	0.00332	0.00332	0.00341
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
2007	0.00893	0.00688	0.01052	0.01087	0.01218
	0.00298	0.00298	0.00305	0.00306	0.00317
	0.00269	0.02103	0.00057	0.00038	0.00012
2008	0.04305	0.04944	0.04453	0.04144	0.05099
	0.00299	0.00303	0.00306	0.00313	0.00328
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
2009	0.02732	0.03714	0.02729	0.03239	0.03829
	0.00297	0.00306	0.00305	0.00308	0.00325
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
2010	0.05552	0.06457	0.05350	0.06102	0.06535
	0.00290	0.00297	0.00298	0.00300	0.00317
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001

Footnotes of the table

a. Modeling the outcome of Asthma (Yes/No).

b. Model statistics are listed, per predictor, as estimated coefficient, standard error of the estimated coefficient, and *p*-value of the Wald's test statistics of the significance of coefficient, respectively.

c. The states of Alaska, Hawaii, and District of Columbia are excluded from the models.

d. Base income level is ≤ $10,000. Unit is in chained (2005) US dollars.

e. Base education level is college and above.

f. Full model – Reduced model.

*N = 3147864 in all models here.

APPENDIX F

SENSITIVITY ANALYSIS

F.1 Mediation Analysis in Logistic Models on Balanced Panel Data

Table F.1 Logistic Regression Estimates [a,b] of Asthma on Fuel Economy and Pollutants, Controlling for Demographic and Health Variables [c] – Balanced Panel

Predictors	**A**	**1**	**2**	**3**	**4**
Intercept	-2.07196	-2.27136	-2.09714	-2.15851	-2.26216
	0.02261	0.02670	0.02310	0.02455	0.02881
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Vehicle Fuel Economy (MPG)	-0.00957	-0.00709	-0.00840	-0.00822	-0.00604
	0.00084	0.00086	0.00085	0.00086	0.00090
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
$PM_{2.5}$		0.00510			0.00255
		0.00036			0.00040
		< 0.0001			< 0.0001
CO			0.00109		0.00523
			0.00094		0.00117
			0.24735		< 0.0001
NO_2				0.00110	0.00041
				0.00013	0.00014
				< 0.0001	0.00322
Age (year)	-0.00802	-0.00798	-0.00816	-0.00804	-0.00816
	0.00013	0.00013	0.00013	0.00014	0.00014
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Caucasian (Yes/No)	0.10136	0.10038	0.10127	0.10452	0.10216
	0.00581	0.00581	0.00591	0.00592	0.00603
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Women (Yes/No)	0.50810	0.50815	0.51243	0.51456	0.51965
	0.00448	0.00448	0.00455	0.00459	0.00466
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
BMI	0.00753	0.00754	0.00757	0.00753	0.00757
	0.00012	0.00012	0.00012	0.00013	0.00013
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Has Health Plan (Yes/No)	0.28478	0.28303	0.29074	0.28960	0.29518
	0.00674	0.00674	0.00685	0.00691	0.00703
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Smoker (Yes/No)	0.16036	0.16123	0.16105	0.15955	0.16106
	0.00505	0.00506	0.00513	0.00518	0.00526
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001

Diabetic	0.43627	0.43585	0.43880	0.43310	0.43577
(Yes/No)	0.00600	0.00600	0.00609	0.00617	0.00627
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Income Level ($) [d]					
10 - < 15k	-0.20740	-0.20707	-0.20748	-0.20905	-0.20894
	0.00949	0.00949	0.00967	0.00977	0.00996
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
15 - < 20k	-0.39236	-0.39153	-0.39144	-0.39021	-0.38866
	0.00925	0.00925	0.00941	0.00951	0.00968
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
20 - < 25k	-0.52325	-0.52286	-0.52437	-0.52138	-0.52215
	0.00909	0.00909	0.00925	0.00934	0.00951
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
25 - < 35k	-0.66909	-0.66872	-0.66881	-0.66591	-0.66524
	0.00891	0.00891	0.00906	0.00915	0.00932
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
35 - < 50k	-0.77444	-0.77423	-0.77503	-0.76827	-0.76822
	0.00884	0.00884	0.00899	0.00907	0.00923
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
50 - < 75k	-0.83895	-0.83940	-0.83805	-0.83255	-0.83089
	0.00908	0.00908	0.00922	0.00931	0.00946
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
>= 75k	-0.90888	-0.91016	-0.91012	-0.90543	-0.90552
	0.00898	0.00898	0.00912	0.00920	0.00934
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Education Level [e]					
No education	-0.16625	-0.16554	-0.18490	-0.16400	0.01402
	0.05819	0.05819	0.05886	0.05903	0.01267
	0.00428	0.00445	0.00168	0.00547	0.26859
Elementary School	0.03245	0.03273	0.01928	0.02802	0.15004
	0.01204	0.01204	0.01232	0.01237	0.00899
	0.00702	0.00654	0.11740	0.02344	< 0.0001
Secondary School	0.15488	0.15341	0.15210	0.15323	-0.10095
	0.00863	0.00863	0.00876	0.00885	0.00596
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
High School	-0.09786	-0.09920	-0.10051	-0.09752	0.04440
	0.00573	0.00573	0.00582	0.00587	0.00570
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Some College	0.04424	0.04371	0.04508	0.04419	-0.18128
	0.00550	0.00550	0.00557	0.00561	0.05973
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.00241
Year (vs 2011)					
2001	-0.15299	-0.17308	-0.15168	-0.16337	-0.17847
	0.00872	0.00884	0.00908	0.00890	0.00944
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
2002	-0.12191	-0.13438	-0.12182	-0.13126	-0.14066
	0.00799	0.00804	0.00819	0.00814	0.00841
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
2003	-0.09219	-0.09903	-0.09379	-0.09956	-0.10740
	0.00755	0.00757	0.00771	0.00763	0.00783
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001

2004	-0.00941	-0.01383	-0.01012	-0.01024	-0.01646
	0.00684	0.00685	0.00695	0.00693	0.00708
	0.16860	0.04336	0.14547	0.13969	0.02011
2005	-0.01366	-0.03451	-0.01474	-0.01843	-0.03246
	0.00645	0.00662	0.00655	0.00653	0.00685
	0.03414	< 0.0001	0.02456	0.00476	< 0.0001
2006	0.02961	0.02781	0.03352	0.02829	0.03172
	0.00641	0.00641	0.00656	0.00656	0.00673
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
2007	0.01943	0.01597	0.02184	0.02364	0.02524
	0.00589	0.00590	0.00604	0.00606	0.00627
	0.00098	0.00678	0.00030	< 0.0001	< 0.0001
2008	0.08641	0.09974	0.08859	0.08349	0.10194
	0.00589	0.00596	0.00602	0.00614	0.00644
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
2009	0.05565	0.07533	0.05712	0.06495	0.07765
	0.00587	0.00604	0.00605	0.00608	0.00642
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
2010	0.11132	0.12949	0.10834	0.12133	0.13065
	0.00569	0.00583	0.00588	0.00588	0.00624
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001

Footnotes of the table

a. Modeling the outcome of Asthma (Yes/No).

b. Model statistics are listed, per predictor, as estimated coefficient, standard error of the estimated coefficient, and *p*-value of the Wald’s test statistics of the significance of coefficient, respectively.

c. The states of Alaska, Hawaii, and District of Columbia are excluded from the models.

d. Base income level is ≤ $10,000. Unit is in chained (2005) US dollars.

e. Base education level is college and above.

f. Full model – Reduced model.

*N = 3147864 in all models here.

F.2 Mediation Analysis Logistic Models Weighted by Sample

Table F.2 Logistic Regression Estimates [a,b] of Asthma on Fuel Economy and Pollutants, Controlling for Demographic and Health Variables [c] – Weighted by Sample

Predictors	**A**	**1**	**2**	**3**	**4**
Intercept	-2.44983	-2.57912	-2.46679	-2.57740	-2.65488
	0.00101	0.00119	0.00102	0.00110	0.00125
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Vehicle Fuel Economy (MPG)	-0.00364	-0.00188	-0.00244	-0.00219	-0.00018
	0.00004	0.00004	0.00004	0.00004	0.00004
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
$PM_{2.5}$		0.00304			0.00183
		0.00001			0.00002
		< 0.0001			< 0.0001
CO			-0.00211		-0.00096
			0.00004		0.00005
			< 0.0001		< 0.0001
NO_2				0.00182	0.00149
				0.00001	0.00001
				< 0.0001	< 0.0001
Age (year)	-0.00616	-0.00613	-0.00619	-0.00612	-0.00614
	0.00001	0.00001	0.00001	0.00001	0.00001
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Caucasian (Yes/No)	0.07766	0.07640	0.07715	0.07972	0.07799
	0.00021	0.00021	0.00021	0.00021	0.00021
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Women (Yes/No)	0.53886	0.53885	0.54005	0.53972	0.54098
	0.00017	0.00017	0.00017	0.00017	0.00017
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
BMI	0.00645	0.00647	0.00645	0.00644	0.00646
	0.00001	0.00001	0.00001	0.00001	0.00001
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Has Health Plan (Yes/No)	0.30633	0.30409	0.30690	0.30735	0.30674
	0.00025	0.00025	0.00025	0.00026	0.00026
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Smoker (Yes/No)	0.19789	0.19884	0.19806	0.19810	0.19887
	0.00020	0.00020	0.00020	0.00020	0.00020
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Diabetic (Yes/No)	0.47691	0.47682	0.47770	0.47603	0.47676
	0.00027	0.00027	0.00027	0.00027	0.00027
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Income Level ($) [d]					
10 - < 15k	-0.19086	-0.19028	-0.19093	-0.19148	-0.19118
	0.00042	0.00042	0.00042	0.00042	0.00043
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
15 - < 20k	-0.29920	-0.29711	-0.29895	-0.29643	-0.29492
	0.00039	0.00039	0.00040	0.00040	0.00040

Predictors	**A**	**1**	**2**	**3**	**4**
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
20 - < 25k	-0.41709	-0.41462	-0.41695	-0.41565	-0.41409
	0.00039	0.00039	0.00039	0.00039	0.00039
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
25 - < 35k	-0.53689	-0.53471	-0.53614	-0.53113	-0.52904
	0.00037	0.00037	0.00038	0.00038	0.00038
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
35 - < 50k	-0.62717	-0.62487	-0.62655	-0.62187	-0.61978
	0.00037	0.00037	0.00037	0.00037	0.00037
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
50 - < 75k	-0.67760	-0.67570	-0.67652	-0.67219	-0.66970
	0.00037	0.00037	0.00037	0.00038	0.00038
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
>= 75k	-0.71927	-0.71763	-0.71860	-0.71504	-0.71271
	0.00036	0.00036	0.00037	0.00037	0.00037
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Education Level [e]					
No education	-0.24280	-0.24087	-0.24502	-0.24868	-0.24934
	0.00206	0.00206	0.00206	0.00208	0.00208
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Elementary School	-0.32246	-0.32606	-0.32721	-0.33427	-0.34110
	0.00050	0.00050	0.00050	0.00051	0.00051
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Secondary School	0.13707	0.13612	0.13682	0.13450	0.13357
	0.00034	0.00034	0.00034	0.00034	0.00035
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
High School	-0.06051	-0.06132	-0.06155	-0.06028	-0.06187
	0.00023	0.00023	0.00024	0.00024	0.00024
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Some College	0.07553	0.07537	0.07603	0.07701	0.07728
	0.00022	0.00022	0.00022	0.00022	0.00022
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Year (vs 2011)					
2001	0.07553	0.07537	0.07603	0.07701	0.07728
	0.00022	0.00022	0.00022	0.00022	0.00022
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
2002	-0.11260	-0.12265	-0.11003	-0.12512	-0.12816
	0.00027	0.00028	0.00028	0.00028	0.00029
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
2003	-0.06743	-0.07081	-0.06646	-0.07428	-0.07497
	0.00026	0.00027	0.00027	0.00027	0.00027
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
2004	-0.00571	-0.00620	-0.00476	-0.00574	-0.00568
	0.00026	0.00026	0.00026	0.00026	0.00026
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
2005	-0.02933	-0.04077	-0.02930	-0.03299	-0.03999
	0.00026	0.00027	0.00026	0.00026	0.00027
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
2006	0.02173	0.02246	0.02329	0.02217	0.02355
	0.00026	0.00026	0.00026	0.00026	0.00026

Predictors	**A**	**1**	**2**	**3**	**4**
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
2007	0.02071	0.01597	0.02185	0.02217	0.02033
	0.00025	0.00025	0.00026	0.00026	0.00026
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
2008	0.06696	0.07451	0.06619	0.06374	0.06938
	0.00025	0.00025	0.00025	0.00025	0.00026
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
2009	0.05922	0.07229	0.05702	0.07035	0.07556
	0.00025	0.00026	0.00026	0.00026	0.00027
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
2010	0.08661	0.09953	0.08225	0.09947	0.10284
	0.00025	0.00026	0.00025	0.00025	0.00027
	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001

Footnotes of the table

a. Modeling the outcome of Asthma (Yes/No).

b. Model statistics are listed, per predictor, as estimated coefficient, standard error of the estimated coefficient, and *p*-value of the Wald’s test statistics of the significance of coefficient, respectively.

c. The states of Alaska, Hawaii, and District of Columbia are excluded from the models.

d. Base income level is ≤ $10,000. Unit is in chained (2005) US dollars.

e. Base education level is college and above.

f. Full model – Reduced model.

*N = 3147864 in all models here.