Erasmus School of Economics

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Master Thesis [Urban, Port and Transport Economics]

On-road transportation and air quality: A quantitative analysis of effects of on-road transportation on fine particulate matter ($PM_{2.5}$) concentrations of U.S. cities

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Abstract

Significant global health challenges are being faced in the 21st century are adverse health impacts attributable to ambient air pollution, where atmospheric fine particulate matter ($PM_{2.5}$) contributes the most to the environmental burden of disease particularly for those living in urban areas. While extensive scientific studies conducted in the last three decades reveal that on-road transportation is one of the significant contributors of $PM_{2.5}$ concentrations in urban areas, more recent studies conversely find that vehicle transportation on the roadways merely represents a relatively small contribution of total $PM_{2.5}$ in the cities due to the continual automotive technology improvement and stringent emission regulations. Such contradiction raises arguments of whether on-road transportation is a major source of ambient $PM_{2.5}$ in urban areas at present and what could be expected from further reduction of on-road transportation emissions to improve urban's air quality in the future. Accordingly, the purpose of this thesis is to clarify such arguments by investigating the causal relationship between on-road transportation and $PM_{2.5}$ concentrations in urban areas based on the most recent available dataset. By performing the instrumental variable estimations with data on 381 U.S. cities from 2001-2016. This thesis finds that on-road transportation does not lead to a significant increase in the overall concentrations of $PM_{2.5}$ in the U.S. cities. For policy implication, the results suggest that the gains from any policy aimed at reducing on-road traffic emissions further to lower $PM_{2.5}$ concentrations in urban areas would be marginal to insignificant.

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Table of Abbreviations

Number

2SLS	Two Stage Least Squares Procedure

A

AADT	Annual Average Daily Traffic
AOD	Aerosol Optical Depth
AQI	U.S. Air Quality Index

B

BEA	U.S. Bureau of Economic Analysis
BLUE	Best Linear Unbiased Estimator
BTEX	Isomers of xylene

C

CAA	Clean Air Act
CBSA	Core Based Statistical Area

D

DAACs	Distributed Active Archive Centers
DARTE	Database of Road Transportation Emission

E

EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency

F

FHWA	U.S. Federal Highway Administration

G

GDP	Gross Domestic Product
GIS	Geographic Information System

H

HPMS	Highway Performance Monitoring System

I

IARC	International Agency for Research on Cancer
IV	Instrumental Variables

L

LEHD	U.S. Census Bureau's Longitudinal Employer-Household Dynamics

M

MISR	Multi-angle Imaging SpectroRadiometer
MODIS	Moderate Resolution Imaging Spectroradiometer

N

NAICS	North American Industry Classification System
NASA	U.S. National Aeronautics and Space Administration

O

OLS	Ordinary Least Squares
OMB	Office of Management and Budget

P

$PM_{2.5}$	Atmospheric fine particulate matter

R

RSC	Royal Society of Chemistry

S

SCR	Selective Catalytic Reduction
SEDAC	Socioeconomic Data and Applications Center
SOA	Secondary Organic Aerosols

U

UNECE	United Nations Economic Commission for Europe

V

VKT	Vehicle Kilometers Traveled
VOCs	Volatile Organic Compounds

W

WHO	World Health Organization

Chemical Compound Formula	
$(NH_4)_2SO_4$	Ammonium sulfate
H_2SO_4	Sulfuric acid
H_2O	Water vapor
NH_3	Ammonia
NH_4^+	Ammonium
NH_4NO_3	Ammonium nitrate
HNO_3	Nitric acid
NO_3^-	Nitrate
NO_x	Nitrogen oxides
OH	Hydroxyl radical
O_2	Oxygen
O_3	Ozone
SO_4^{2-}	Sulfate
SO_2	Sulfur dioxides
SO_x	Sulfur oxides

1. Introduction

Significant global health challenges are being faced in the 21st century, ranging from outbreaks of vaccine-preventable diseases, increasing rates of non-communicable diseases, obesity and physical inactivity to unintentional injuries and health impacts attributable to the environmental pollutants (World Health Organization [WHO], 2019). Apart from the ongoing global pandemic of coronavirus disease (COVID-19), which scourged one of the most significant rapid losses of life and severe economic recession (McKibbin & Fernando, 2020), ambient air pollution is, in actual fact, the greatest environmental health threat due to it stimulates the most morbidity and mortality (Manisalidis et al., 2020; WHO, 2019). According to the World Health Organization (2019), every day nine out of ten people globally breathe polluted air. Of these, the adverse health implications attributable to ambient air pollution exposure are particularly critical for those living in urban areas where tailpipe emissions, the crucial negative externalities of road transport, are one of the greatest contributors imposing to the overall deterioration of air quality (Amato et al., 2014; Grange et al., 2017; Manisalidis et al., 2020; Pant & Harrison, 2013; von Schneidemesser et al., 2019).

Ambient air pollution causes and aggravates various non-communicable diseases, scourging around 7 million premature deaths annually (WHO, 2019). According to the American Thoracic Society (2019), the effects of short-term exposure to ambient air pollution are temporary. The symptoms range from slight physical discomfort such as shortness of breath, coughing, wheezing, and skin irritation to a greater extent severe states like pneumonia and asthma, particularly those susceptible and vulnerable populations (Lui et al., 2019). These symptoms can be exacerbated over the long-term ambient air pollution exposure, causing permanent respiratory diseases such as chronic asthma and cardiovascular diseases like myocardial infarction, heart failure, and pulmonary insufficiency (Manisalidis et al., 2020). Apart from major respiratory and cardiovascular diseases, ambient air pollution, especially atmospheric fine particulate matter ($PM_{2.5}$), one of the six key primary air pollutants[1], has been defined as carcinogenic to humans by the International Agency for Research on Cancer (IARC) (Loomis et al., 2013). As a consequence, ambient air pollution contributes the most to the environmental burden of disease, which urgently prompts international cooperation for repeated calls to rethink approaches to mitigation (Giles-Corti et al., 2016; United Nations Economic Commission for Europe [UNECE], n.d.).

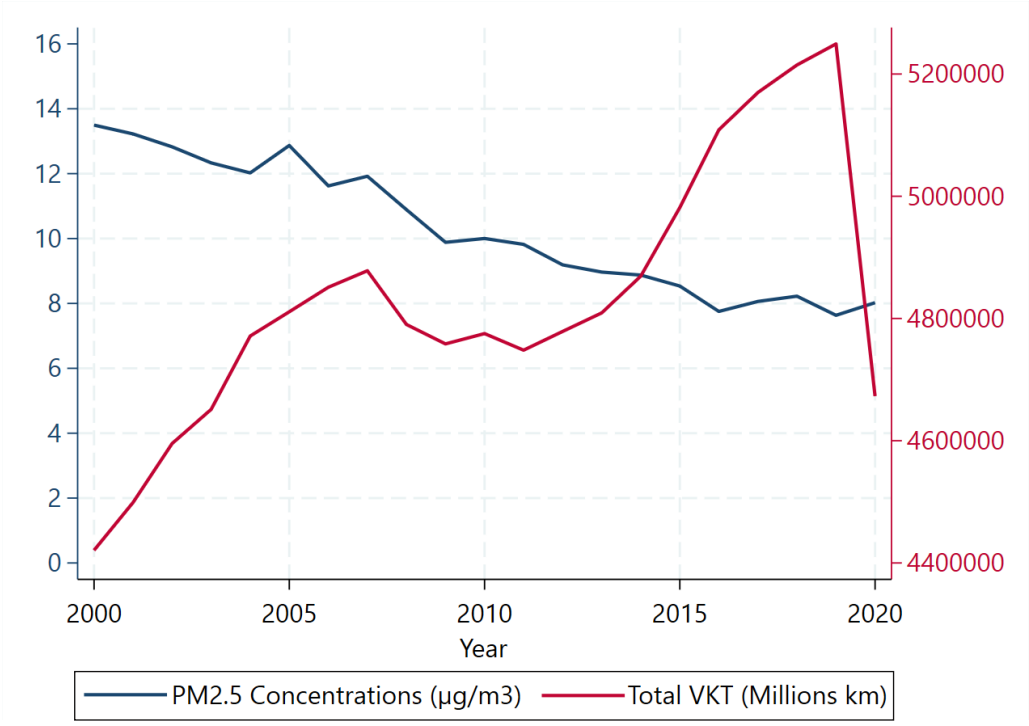
Focus on the atmospheric fine particulate matter, the most dangerous air pollutants that constitutes one of the most significant challenging problems for health, air quality, and climate change policy (Fuzzi et al., 2015). Extensive scientific studies conducted in the last

[1] According to the World Health Organization (WHO), six major air pollutants are particulate matter, ground-level ozone, carbon monoxide, sulfur dioxides, nitrogen dioxides, and lead (United States Environmental Protection Agency, n.d.).

three decades reveal that the negative externality of on-road transportation is one of the primary pollution sources imposing an appreciable approximately 25 percent contribution to total $PM_{2.5}$ concentrations in urban areas globally (Amato et al., 2014; Davidson et al., 2005; Hodan & Barnard, 2004; Karagulian et al., 2015; Pant & Harrison, 2013). However, there are substantial differences in the cities' $PM_{2.5}$ concentrations contributed by on-road transportation across regions. In developing countries such as China, India, Brazil, and Southeast Asia countries, the operation of on-road vehicles accounts for up to 34-37 percent of total $PM_{2.5}$ concentrations. In contrast, in developed countries like the United States, Western Europe, Japan, and the Nordic countries, on-road transportation contributes much less to $PM_{2.5}$ concentrations, ranging between 21-24 percent in total (Karagulian et al., 2015). This lower $PM_{2.5}$ concentration attributable to the negative externalities of on-road transportation in developed counties is primarily due to several decades of cleaner automotive technology improvement, clean air action, and stringent regulations that have been implemented in such countries (Mathissen et al., 2011; Thorpe & Harrison, 2008; Winkler et al., 2018).

Figure 1.1

Average annual $PM_{2.5}$ concentrations and total vehicle kilometers travelled (VKT) in the U.S. during 2000-2020



Note. The left x-axis is the concentration scale in µg/m³, while the right x-axis is the scale of total vehicle kilometers traveled (VKT) in a million kilometers. It is noted that there is a sudden drop in total VKT in 2020. This is due to a lockdown regulation to combat the COVID-19 pandemic. The annual $PM_{2.5}$ concentrations are retrieved from the U.S. Environmental Protection Agency (EPA). The total vehicle kilometers traveled is obtained from the U.S. Federal Highway Administration (FHWA).

For example, in the U.S., economic instruments of command-and-control policies for addressing the problem of transport externalities such as vehicle emission and fuel standards began regulating in the 1970s. These federal emission standards are set through a combination of legislative mandates of Clean Air Act (CAA) amendments, regulations managed by the Environmental Protection Agency (EPA), and as well as improvement of cleaner engine technologies (e.g., three-way catalytic converters, lean nitrogen oxides traps, selective catalytic reduction, and diesel particulate filters) imposed to the automotive industry (The U.S. Environmental Protection Agency [EPA], n.d.). Currently, the federal Tier 3 emission standards for light-duty vehicles and the closely aligned California LEV III standards are phased in from 2017 through 2025 (Winkler et al., 2018; EPA, n.d.). As a result of the stringent regulations and automotive technology improvements, ambient concentrations of $PM_{2.5}$ in most cities in the U.S. have dropped significantly, roughly up to 41 percent since 2000, despite the continued growth of the total mileage driven (as shown in Figure 1.1) (Mathissen et al., 2011; The U.S. Federal Highway Administration [FHWA], n.d.; Thorpe & Harrison, 2008).

While a number of scientific studies conducted in the last three decades indicate that on-road transportation is one of the significant contributors to $PM_{2.5}$ concentrations in urban areas, more recent studies, on the other hand, find that vehicle transportation on the roadways is now merely representing a relatively small contribution of total $PM_{2.5}$ in the cities, where again automotive technology improvement, clean air action, and stringent regulations have been major factors to a reduction $PM_{2.5}$ concentrations trend (Harrison et al., 2021; Li & Managi, 2021). As a consequence of the recent finding, this raises arguments among scientists about whether on-road transportation is a major source of cities' air pollution at present, and what could be expected from further reduction of on-road transportation emissions to improve urban's air quality in the future (Amato et al., 2014; Grange et al., 2017; Harrison et al., 2021; Hong-Li et al., 2017; Pant & Harrison, 2013; Winkler et al., 2018). This thesis, therefore, is built inspired by such arguments and an attempt to mitigate ambient air pollution in urban areas. Consequently, this thesis aims to clarify whether on-road transportation is a significant source of ambient concentrations of $PM_{2.5}$ in urban areas based on the most recent available dataset and to understand the potential to reduce on-road traffic emissions further to improve air quality. To achieve the research objectives, the causal relationship between on-road transportation and the level of ambient fine particulate matter ($PM_{2.5}$) concentrations across U.S. metropolitan areas is investigated by employing the most recent dataset that covers advanced automotive cleaner technologies and stringent emission standards (e.g., the federal Tier 2 and 3 emission standards and the California LEV II and III regulations). Accordingly, this thesis seeks to answer the following research question:

"Based on the most recent dataset, is emissions from on-road transportation a pollution source that significantly contributes to fine particulate matter ($PM_{2.5}$) concentrations in urban areas?".

This thesis provides several important contributions to the existing literature and policy-making relevance in several ways. Firstly, this study will provide insights into the causal effects of on-road transportation on ambient $PM_{2.5}$ concentrations in urban areas, where total vehicle kilometer traveled (VKT) is employed as an indicator of on-road vehicle usage. Although a large number of atmospheric science research has been conducted about the contribution of on-road transportation to the deterioration of air quality in the last three decades, studies covering a more recent dataset on on-road transportation and concentrations of $PM_{2.5}$ are limited. Consequently, there is insufficient recent formal statistical evidence regarding the association between on-road transportation and $PM_{2.5}$ concentrations in urban areas. Among the existing literature, the paper closest to this thesis is Li and Managi (2021), which studies the quantitative association of annually county-level $PM_{2.5}$ concentrations with on-road transportation across the contiguous United States. However, the paper employed average on-road CO_2 emission to measure on-road transportation. In addition, Li and Managi cover the scope of their empirical analysis that included non-urban areas, where source appointment, chemical composition, and the formation of $PM_{2.5}$ are considerably different from those in the urban areas. Consequently, conducting this thesis will help address the current shortage of research in urban environments.

Secondly, as mentioned earlier, the reduction $PM_{2.5}$ concentrations trend despite the growing tendency of the total mileage driven raises arguments among scientists towards whether emission from the road vehicle fleets is a significant source of $PM_{2.5}$ in urban areas. The contributions of this thesis that throw light on the most recent empirical evidence of the effect of on-road transportation on ambient $PM_{2.5}$ concentrations will potentially support future researchers in clarifying the significance of cities' ambient $PM_{2.5}$ concentrations attributable to on-road transportation. Furthermore, air pollution such as $PM_{2.5}$ is a critical negative externality of road transport (Santos et al., 2010). To date, economic instruments of command-and-control approaches such as those vehicle emissions and fuel standards in the U.S. and the European emission standards are the most widely used policy for addressing the problem of transport externalities (Santos et al., 2010). The results of this thesis will help policymakers address the optimal transport policy and understand the potential of implementing the command-and-control policies in the reduction of the negative externality of road transport to improve urban air quality in the future.

The remainder of this thesis paper is structured as follows: Section 2 is the theoretical framework providing a rich understanding of the atmospheric particulate matters, including source apportionment, physical and chemical characteristics of $PM_{2.5}$, as well as a review of relevant studies, that is crucial in developing the research hypothesis. In Section 3, data and descriptive statistics are described, followed by methodology, and statistical analysis results are presented in Section 4 and 5, respectively. Section 6 discusses the research's findings,

policy implications, limitations, and suggestions for future research. Lastly, the conclusion of this thesis paper is summarized in Section 7.

2. Theoretical Framework

Atmospheric particulate matter is a highly variable and complex mixture of aerosol particles and chemical species. Although a significant amount of research conducted in the last three decades has been revealed that on-road transportation is a major source contributing to total $PM_{2.5}$ concentrations in urban areas (Amato et al., 2014; Grange et al., 2017; Pant & Harrison, 2013), assessment of how and to what extent to which on-road transportation contributes to $PM_{2.5}$ in urban areas are difficult to quantify and not straight forward (Hodan & Barnard, 2004; Davidson et al., 2005). This is because $PM_{2.5}$ concentrations have temporal, seasonal and spatial variations, which depend primarily on a complex interplay between various factors, including altitude, the number of anthropogenic activities, geographic attributes, meteorological conditions, and atmospheric conditions present in a particular place. Thereby, in order to understand the contribution of on-road transportation, especially in the scope of driving and mileage, to the urban environment, it is essential to understand various relevant aspects of the atmospheric particulate matters, such as sources, chemical characteristics, chemical compositions, and their formation. Accordingly, in this theoretical framework, this thesis starts by providing the fundamental knowledge of atmospheric particulate matter. This section includes source apportionment, physical and chemical characteristics of $PM_{2.5}$. The second section discusses the contribution of on-road transportation to $PM_{2.5}$ concentrations in urban environments through the three general processes, followed by a review of relevant recent studies that investigate the causal relationship between on-read transportation (i.e., in an aspect of driving and mileage) and concentrations of $PM_{2.5}$ in the third section. Lastly, the research hypothesis is formulated based on the relevant theory from atmospheric science and existing studies.

2.1 Source apportionment, physical and chemical characteristics of $PM_{2.5}$

Atmospheric particulate matter or particles in the atmosphere is a central component of the atmospheric chemical and climate system, a component of biological systems and global biogeochemical cycles, and a significant air pollutant posing adverse effects on human health (Royal Society of Chemistry [RSC], 2014). The term *"particulate matter"* or "*PM"*, according to Seinfeld and Pandis (2016), Page 47, is "an aerosol particle may consist of a single continuous unit of solid or liquid containing many molecules held together by intermolecular forces and primarily larger than molecular dimensions (>0.001 μm); a particle may also consist of two or more such unit structures held together by inter particles adhesive forces such that it behaves as a single unit in suspension or on deposit". Whereas an *"aerosol"* is technically defined as a

tiny particle dispersed in gases, often usage refers to the aerosol as the particle component only (Seinfeld & Pandis, 2016).

Atmospheric aerosol particles have a range of shapes and morphologies. Generally, atmospheric aerosols are particles ranging in size from a few nanometers (nm) to ten micrometers (μm) in diameter. Based on their size, atmospheric aerosol particles are commonly distributed into a trimodal mode; (i) an ultra-fine or a nucleation mode (<0.01 μm diameter), (ii) a fine or an accumulation mode (0.01-2.5 μm diameter), and (iii) a coarse mode (2.5-10 μm diameter) (Seinfeld & Pandis, 2016). Accordingly, fine particulate matter, commonly known as $PM_{2.5}$, is the atmospheric aerosol particles with aerodynamic diameters ranging between 0.01-2.5 μm.

Particles in the atmosphere are a highly variable and complex mixture of aerosol particles and species. According to the atmospheric science studies, atmospheric aerosol particles are generated by direct particle emissions from natural sources, such as windborne dust, soil dust, sea salt, biological debris and volcanoes, and by anthropogenic activities, such as the combustion of fuels and agricultural activities; all of these direct particle emissions are often referred to as *primary aerosol*. Apart from being emitted directly as particles, atmospheric aerosol particles can also arise from a formation of gaseous precursor emissions in the atmosphere through the chemical gas-to-particle conversion process. Particles that are resulted from the gases formation are referred to as *secondary aerosol* (Seinfeld & Pandis, 2016).

Table 2.1 demonstrates a range of emission estimates of atmospheric aerosol particles originating from natural and anthropogenic sources on a global basis. According to Table 2.1, a significant large portion of atmospheric aerosol particles globally is emitted by natural sources, accounting for approximately 98 percent in total. However, most natural-origin aerosol particles are in the coarse mode, which poses much less harmful to human health than fine particles (Zanobetti & Schwartz, 2009). Concerning only the fine particulate matter, most primary $PM_{2.5}$ are released in the carbonaceous-based aerosol (e.g., element carbon or black carbon) or mineral-based aerosol. In contrast, most secondary $PM_{2.5}$ is the tropospheric aerosols comprising of sulfate, nitrate, ammonium, and compounds of carbonaceous-based aerosols such as organic carbon, of which approximately 86 percent of $PM_{2.5}$ (both primary and secondary) globally are anthropogenic origin (Hyslop, 2009; Seinfeld & Pandis, 2016). In the U.S., a recent study reveals that anthropogenic activities contribute to almost 90 percent of total $PM_{2.5}$ in the urban areas, of which unspecified sources of human origin contributes about 46 percent, followed by 24 percent from traffic, 12 percent from domestic fuel burning, and only 9 percent from industries, respectively (Karagulian et al., 2015). However, the study did not quantify the category of cities' $PM_{2.5}$ as primary and secondary. To get an estimated fraction of primary $PM_{2.5}$ and secondary $PM_{2.5}$ attributable to especially transport sectors, we refer to the EPA National Emissions Inventory report in 1999. According to Table 2.2, on-road

Table 2.1

Global emissions estimates from major atmospheric aerosol particles source appointment

Emission Sources	Estimated flux (Tg yr^{-1})	Particle size mode
Natural		
Primary		
Soil dust	2,980	Fine and coarse
Sea salt	10,100	Mainly coarse
Volcanic dust	30	Coarse
Biological debris	50	Coarse
Secondary		
Sulfates from DMS	12.4	Fine
Sulfates from volcanic SO_2	20	Fine
Organic aerosol from biogenic VOCs	11.2	Fine
Anthropogenic		
Primary		
Industrial dust (except black carbon)	100	Fine and coarse
Black carbon	12	Fine
Organic aerosol	81	Fine
Secondary		
Sulfates from SO_x	48.6	Fine
Nitrate from NO_x	21.3	Fine and coarse

Note. The terminology of aerosols is defined as tiny particles dispersed in gases. Dust is suspensions of solid particles produced by mechanical disintegration of material such as crushing, grinding, and blasting; aerodynamic diameter > 1 μm. Soot is agglomerations of particles of carbon impregnated with "tar", formed in the incomplete combustion of carbonaceous material. Fine particles have an aerodynamic diameter of 2.5 μm or less, while coarse particles have diameters generally larger than 2.5 μm and smaller than or equal to 10 μm. *Source.* Adapted from Seinfeld and Pandis (2016), Table 2.21, P.54.

Table 2.2

Primary $PM_{2.5}$ and $PM_{2.5}$ Precursors Emitted in the US in 1999, in million tons

Emission Sources	VOCs	NO_x	SO_x	NH_3	Primary $PM_{2.5}$
Stationary fuel combustion	1.447	9.586	15.513	0.074	1.040
Industrial	1.266	0.781	1.313	0.155	0.447
Solv/Store/Waste/Misc.	8.235	0.541	0.051	0.098	0.515
Off-road transportation	2.829	4.417	0.444	0.035	0.318
On-road transportation	5.612	8.347	0.300	0.263	0.184
Agriculture crops	0	0	0	0.723	0.871
Agriculture livestock	0	0	0	3.585	0.086
Fires	0	0	0	0	1.196
Paved roads	0	0	0	0	0.628
Unpaved roads	0	0	0	0	1.097
Other fugitive	0	0	0	0	0.525
Total	**19.391**	**23.674**	**17.623**	**0.627**	**2.505**

Note. Source: EPA National Emissions Inventory report (1999).

transportation contributes approximately 23 percent of total $PM_{2.5}$ in the U.S., of which 14 percent is classified as the primary $PM_{2.5}$ and the rest 86 percent is the secondary $PM_{2.5}$.

In addition to types of atmospheric aerosol particles and their source appointment; size distribution, chemical composition, and mass vary by location depending on altitude, the number of anthropogenic activities, geographic attributes, meteorological conditions, and atmospheric conditions present in a particular place (Davidson et al., 2005). These variations ultimately affect the formation and life cycle of aerosol particles yielding different concentrations of $PM_{2.5}$ in different places (Davidson et al., 2005; Seinfeld & Pandis, 2016).

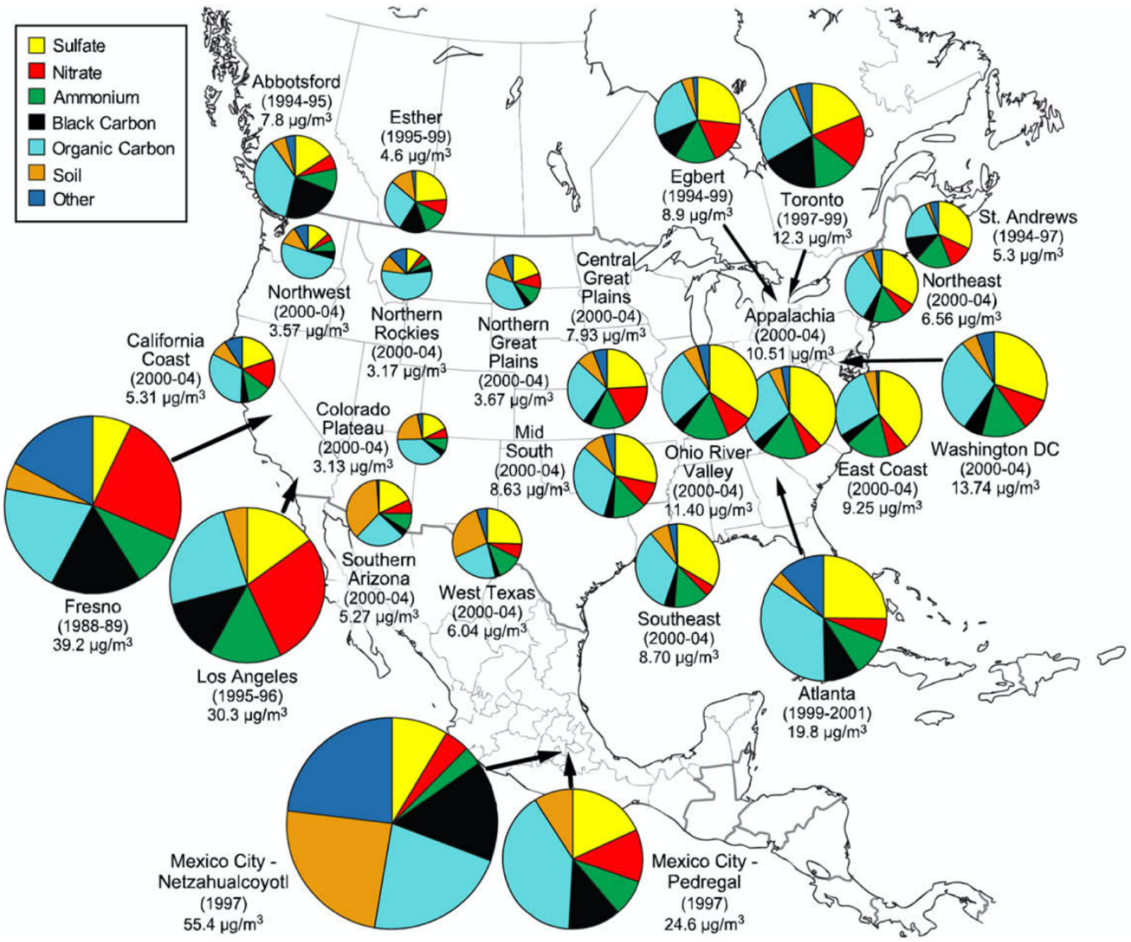
Generally, the chemical composition of atmospheric aerosol particles in the typical urban area comprises of natural crustal materials (e.g., carbonates and silicates), inorganic constituents or minerals (e.g., sulfate, nitrate, ammonium, sodium, potassium, and chloride), trace metals (found in fuels and derived from crustal sources and vehicle brake and tire wear), and organic components—the latter consist of both elemental and organic carbon. Elemental carbon, often known as black carbon, is emitted predominantly by incomplete combustion. Organic carbon can result from atmospheric oxidation and subsequent condensation of low-volatility organic compounds. Volatile organic compounds (VOCs) are chemical compounds that included a variety of both natural and synthetic substances. They are emitted as gases where the predominant chemical element is hydrocarbons. VOCs are described as volatile due to their properties of high vapor pressure and low water solubility, making the compounds easily evaporate, releasing molecules into the atmosphere (EPA, n.d.). Currently, there are more than 300 different kinds of VOCs that can be detected by chromatography (Han & Naeher, 2006). Among them, traffic-related VOCs posing a carcinogenic to human are the aromatic compounds such as benzene, toluene, ethylbenzene, and isomers of xylene (BTEX). Ammonia, primarily derived from agriculture, readily liquefies in aqueous particles and neutralizes sulfate and nitrate, usually found as ammonium sulfate or ammonium nitrate in urban regions (RSC, 2014; Seinfeld & Pandis, 2016).

Figure 2.1 shows a schematic diagram of the composition of $PM_{2.5}$ at various sites in the United States, Canada, and Mexico. According to Figure 2.1, the chemical composition of $PM_{2.5}$ in the U.S. is dominated by sulfate (SO_4^{2-}), nitrate (NO_3^-), ammonium (NH_4^+) (resulting from sulfur oxides (SO_x), nitrogen oxides (NO_x), and ammonia (NH_3), respectively), and organic carbonaceous components (e.g., black and organic carbon). In the West, nitrate and carbonaceous-based compounds are the most abundant chemical species, while in the East, the most abundant chemical species in $PM_{2.5}$ are sulfate and carbon-based compounds. Nevertheless, in terms of the absolute magnitude, it has a temporal and seasonal reliance based on the species' volatility and the impact of the photochemical reaction of the secondary aerosols. The "other" category includes aerosol particles such as natural bioaerosols (e.g.,

microbial, plant, and animal sources), and water associated with the aerosol particles (Davidson et al., 2005).

Figure 2.1

Schematic diagram of chemical composition of $PM_{2.5}$ at several urban and rural locations



Note. Figure is retrieved from Hyslop (2009), P.187.

2.2 Contribution of on-road transpiration to $PM_{2.5}$ in urban areas

On-road transportation contributes to ambient $PM_{2.5}$ concentration levels through three general processes: (i) a direct emission from the vehicle tailpipes (exhaust emissions), (ii) emissions due to wear and tear of vehicle parts and re-suspension of dust (non-exhaust emissions), and (iii) a formation of traffic-emitted gaseous precursor emissions in the atmosphere through the chemical gas-to-particle conversion process. $PM_{2.5}$ emitted from process (i) and (ii) are typically referred to as *primary $PM_{2.5}$*, whilst formed from process (iii) is generally known as *secondary $PM_{2.5}$* (Han & Naeher, 2006; Pant & Harrison, 2013; Amato et al., 2014).

Contribution of on-road transpiration to primary $PM_{2.5}$

To begin with the first contribution process, primary $PM_{2.5}$ particles emitted directly from the exhaust tailpipes of on-road vehicles can be visible as white or black smoke, especially if the particles are emitted in a sufficient vast quantity. Even though all types of on-road combustion engines release a certain amount of particulate matter, on-road diesel-powered vehicles are known to be the key source of $PM_{2.5}$ emissions in the transportation sector with typically light- and heavy-duty trucks playing the largest role (Klimont et al., 2017). In addition, atmospheric aerosol particles emissions from diesel-powered and gasoline-powered vehicles are different in terms of composition; diesel-powered vehicles release both a more significant mass of fine and ultra-fine modes of aerosol particles compared to gasoline-powered vehicles (Rose et al., 2006). Likewise, diesel-powered vehicles is extensively found for releasing a considerable higher amount of black smoke, approximately six to ten times, than gasoline-powered vehicles, which typically emits white smoke (Watson et al., 1994; Weingartner et al., 1997; Ntziachristos et al., 2007).

Regarding the second process, non-exhaust atmospheric aerosol particles consist of various emissions that do not derive from a vehicle's tailpipe. These include aerosol particles generated from the abrasion of tire wear, brake wear and road surface, the corrosion of other vehicle components such as the clutch, and the resuspension of road dust (Pant & Harrison, 2013). Although these non-exhaust emissions represent a relatively small share of the total $PM_{2.5}$ from on-road traffic-related as they contribute mainly to the coarse mode of aerosol particles, their importance recently gained more attention due to little to no policies or technologies implemented to reduce wear emissions or resuspension in the past (Kuhlbusch et al., 2009; Amato et al., 2012; Harrison et al., 2011, 2012b; Denier van der Gon et al., 2013). In contrast to exhaust emissions, many of the research and policy actions in the last few decades has focused on the development of cleaner automotive technologies and stringent regulations, resulting in a significant drop in total ambient aerosol particles from exhaust emissions of road transport over time, despite an increase in total kilometers driven (Thorpe & Harrison, 2008; Mathissen et al., 2011).

Generally, non-exhaust emissions are enriched in trace metals (e.g., Cu, Zn, Ba, Sb, Mn) and contain fewer organic carbonaceous components (Amato et al., 2009; El Haddad et al., 2009; Gietl et al., 2010). According to Harrison et al. (2012), a study at the Marylebone Road sampling site, London, reported that the size distributions of trace metals were indicative of aerosol sources. Keuken et al. (2010) conducted research on traffic-related PM in the Netherlands concluded that resuspension of accumulated deposited PM and road wear-related particles are the primary sources of non-exhaust emissions; meanwhile, tire wear and brake wear contribute to zinc (Zn) and copper (Cu) respectively. Nevertheless, Narváez et al. (2008) showed that even though most particles arise from tire wear, brake wear, and road surface abrasion are in coarse mode, abrasion of such can contribute significantly to $PM_{2.5}$.

Concerning road dust and road surface wear, a study held in Monterrey, Mexico, showed that re-suspended dust was found to be contributing almost 20-25 percent to total $PM_{2.5}$ (Mancilla & Mendoza, 2012). However, many studies (e.g., Gertler et al., 2006; Thorpe et al., 2007; Laidlaw et al., 2012) argued that contribution of re-suspended road dust particles has a regional and seasonal variable which heavily influenced by various parameters such as vehicle movement (particularly traffic speed), street maintenance, meteorological parameters and speed of traffic. Likewise, concentrations of trace metals in non-exhaust particles also varies based on many factors, including traffic volume and pattern, vehicle fleet characteristics, driving and traffic patterns, and meteorological and geological conditions of the region (Omstedt et al., 2005; Amato et al., 2011a,b; Duong and Lee, 2011).

Contribution of on-road transportation to secondary $PM_{2.5}$

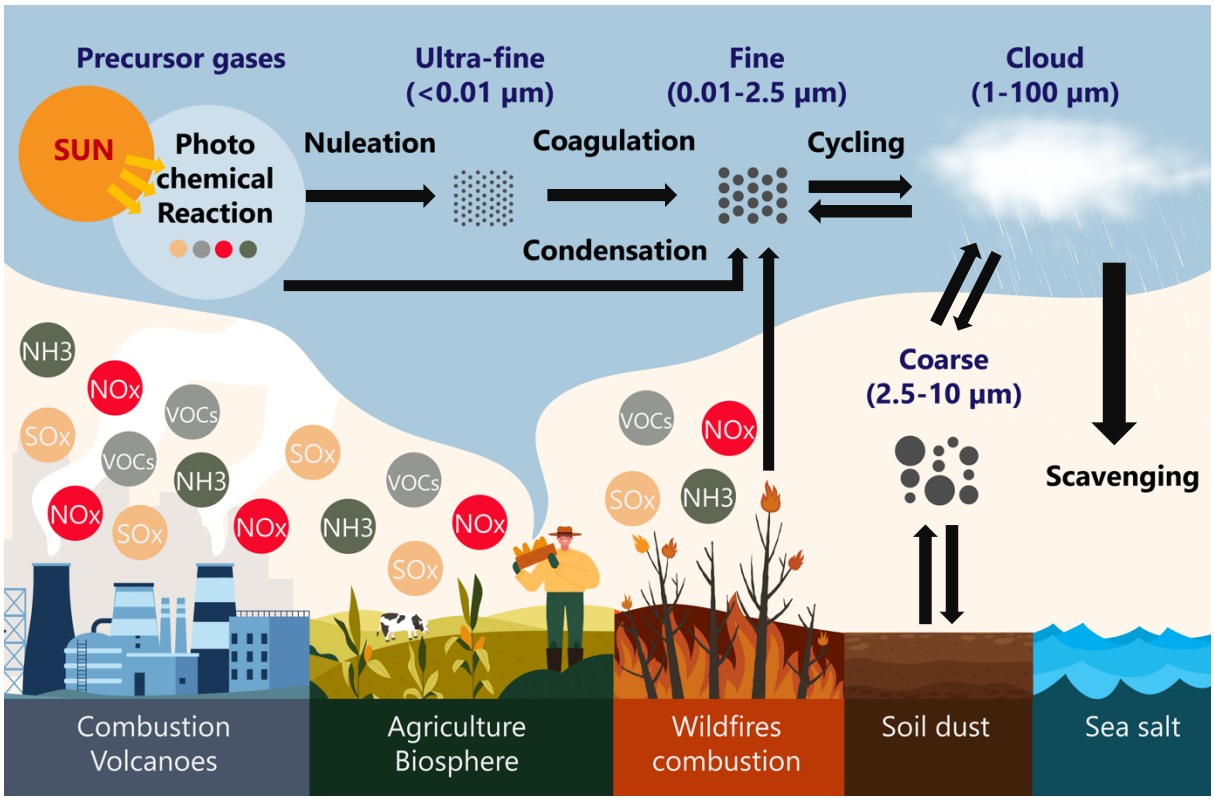
Concerning the third contribution process, apart from direct exhaust and non-exhaust emissions, incomplete fuels combustion of vehicle engines moreover emit several exhaust gases such as volatile organic compounds (VOCs), nitrogen oxides (NO and NO_2, together called NO_x), sulfur oxides (SO_x), and ammonia (NH_3). These exhaust gases, albeit a relatively small part of combustion gases, are noxious or toxic substances that threaten human health, and more importantly, they have been considered the most significant $PM_{2.5}$ precursor pollutants (EPA, 1999; McMurry et al., 2004; Davidson et al., 2005). According to the atmospheric science studies, the secondary $PM_{2.5}$ is subsequently formed within the atmosphere as a result of a photochemical reaction, nucleation, coagulation, condensation, and other atmospheric processes between the precursor pollutants after exiting through the exhaust stream of vehicle tailpipes (Kelly & Fussell, 2012).

Figure 2.2 illustrates life cycles and the formation process of the secondary $PM_{2.5}$. According to Figure 2.2, the life cycles of the secondary $PM_{2.5}$ begins a formation by nucleation process. *"Nucleation"* is a chemical reaction occurring when precursor pollutants, predominantly volatile organic compounds (VOCs), nitrogen oxides (NO_x), sulfur oxides (SO_x), and ammonia (NH_3), begin to form particles, typically at the ultra-fine mode (aerodynamic < 0.01 μm diameter), by accumulating existing droplets of the inorganic and organic vapors around them. This chemical reaction process is initiated by the absorption of energy in light (e.g., ultraviolet, visible light, or infrared radiation). The consequence of molecules' absorbing lights creates transient excited states, allowing chemical species to fall apart, change to new structures, or combine with each other or other molecules. Next, these ultra-fine particles are further transformed by the coagulation process. *"Coagulation"* is a process that aggregates finely divided particles together and forms large flocs (Chang, 2016). Furthermore, this term is typically employed to describe the cooling of exhaust gases, causing the conversion of some exhaust vapors into particles (Hodan & Barnard, 2004). Additionally, according to atmospheric science studies, the coagulation process albeit influences the

formation of $PM_{2.5}$. It can lead to the settling of some particulate matter, hence drawing those particulate matter from the atmosphere. For particles that are not removed by the coagulation process, they subsequently have a chemical interaction with other chemical species or vapors, e.g., sulfuric acid (H_2SO_4), nitric acid (HNO_3), and ammonia (NH_3), leading the particle to grow in aerodynamic diameter (Hodan & Barnard, 2004). Ultimately, the coagulation process with optimal environmental conditions can lead to particle formation that is too large to remain airborne resettled to the land. This process is thus one of the mechanisms that regulate the PM concentration levels in the atmosphere (Hodan & Barnard, 2004; Seinfeld & Pandis, 2016).

Figure 2.2

Life cycles of the atmospheric particulate matter



Note. Adapted from Fuzzi et al. (2015).

Focusing in detail on the formulation of $PM_{2.5}$ from traffic-emitted VOCs precursors, VOCs gases in the atmosphere are often oxidized by species such as the hydroxyl radical (OH) and ozone (O_3), yielding the secondary organic aerosols (SOA), which are one type of $PM_{2.5}$. However, the products from VOCs oxidization are not always transformed into fine particles. Only the oxidation products with low volatilities and further deposits on existing particles will become a $PM_{2.5}$, which depends on several factors such as atmospheric abundance, chemical reactivity, oxidant availability, and product volatility present in the atmosphere at given time oxidation occurs (Hodan & Barnard, 2004).

Referring to Table 2.2, the EPA National Emissions Inventory (1999) reports that on-road vehicle sources contribute a significant amount of $PM_{2.5}$ precursor VOCs, taking up approximately 30 percent of the total VOCs in the U.S. In line with an investigation in Baltimore metropolitan area, Maryland, the study showed that on-road vehicle exhaust contributed approximately 29 percent of the VOCs in the area (Hodan & Barnard, 2004). Although these studies quantify the estimated contributions of on-road transportation to ambient VOCs, there are no estimates of how much of the VOCs from on-road transportation results in the formation of $PM_{2.5}$.

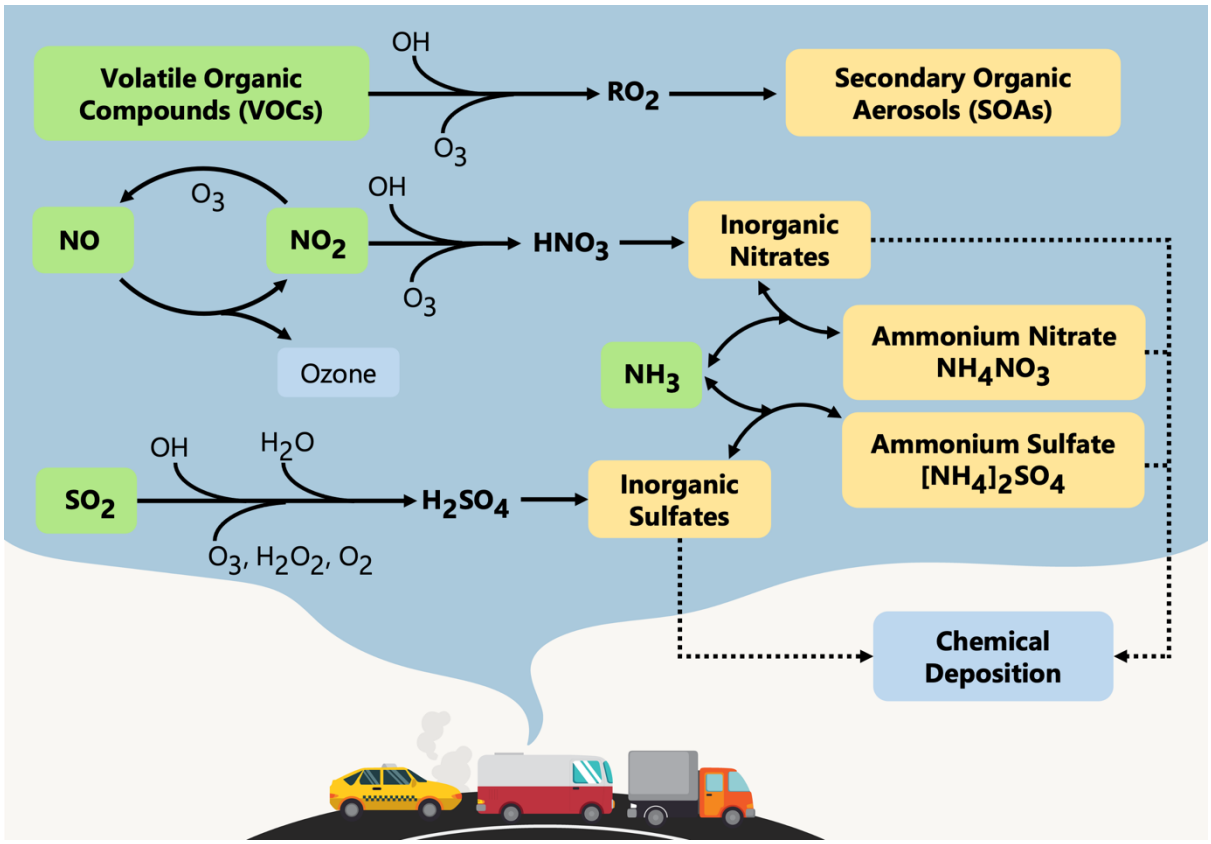
Apart from VOCs, significant amounts of $PM_{2.5}$ are also formed from nitrogen oxides, sulfur oxides, and ammonia. According to the Northern Front Range Air Quality Study (NFRAQS) in Colorado by Watson et al. (1998), NO_x emissions from combustion sources are comprised mostly of nitric oxide (NO), while SO_x emissions are mostly gas-phase sulfur dioxide (SO_2). Similar to VOCs, both NO_x and SO_x must be oxidized, generally by species like the hydroxyl radical (OH), ozone (O_3), oxygen (O_2), and water vapor (H_2O) before becoming fine particulate nitrate and sulfate. Given the same amount of traffic-emitted nitrogen oxides, sulfur oxides, and ammonia across the U.S. regions, concentrations of $PM_{2.5}$, resulting from the formation of these precursor pollutants, have seasonal and regional variation. This difference is primarily due to atmospheric conditions (Watson et al., 1998). In the wintertime, $PM_{2.5}$ formed from nitrogen oxides and sulfur oxides are limited by the abundance of atmospheric oxidizers and water vapor. As illustrated in Figure 2.3, nitric oxide (NO) and sulfur dioxide (SO_2) have to be oxidized transforming into nitric acid (HNO_3) and sulfuric acid (H_2SO_4), respectively, prior to chemical reaction with other substances to form $PM_{2.5}$; nevertheless, the atmospheric conditions in winter are not favorable for the formation of nitric acid in most areas of the U.S. In the contrarily, ammonia can directly form $PM_{2.5}$ as ammonium nitrate (NH_4NO_3) and ammonium sulfate [$(NH_4)_2SO_4$] in the wintertime. In contrast, this chemical reaction is reversed by higher temperatures in summertime (McMurry et al., 2004). This implies that traffic-emitted NO_x and SO_x would considerably contribute to $PM_{2.5}$ formation during summertime and in warmer winter climates such as in the southern states. In addition to nitrogen oxide and sulfur dioxide, this formulation of $PM_{2.5}$ from ammonia suggests that regions with higher ammonia emissions, primarily emitted from agricultural activities, have higher $PM_{2.5}$ concentrations during wintertime when $PM_{2.5}$ formation from nitrogen oxide and sulfur dioxide are not active.

Referring again to Table 2.2, the EPA's National Emission Inventory (1999) shows that on-road vehicles usage contribute a significant amount of $PM_{2.5}$ precursor NO_x, accounting for about 35 percent of totals. On the other hand, it only contribute a small portion of $PM_{2.5}$ precursor SO_2 especially when compared to stationary source fuel combustion categories.

Likewise, $PM_{2.5}$ precursor ammonia are released in a minimal amount from on-road vehicles usage compared to agriculture activities. It is noted, however, that contribution of on-road vehicle usage toward the production of $PM_{2.5}$ from the secondary chemical gas-to-particle conversion process was not quantified in the original report. What only observed in the report are the amount of $PM_{2.5}$ precursor pollutants that were contributed by transport sectors.

Figure 2.3

Chemical reaction of $PM_{2.5}$ precursor pollutants in the $PM_{2.5}$ formation process



Note. The significant traffic-emitted *$PM_{2.5}$* precursors are shown in *green squares*. *Yellow squares* are the $PM_{2.5}$ resulting from the chemical formation process. Adapted from McMurry et al. (2004).

Assessments of the relationship and the degree to which on-road vehicle usage really contributes to $PM_{2.5}$ in urban areas is difficult to quantify (Hodan & Barnard, 2004; Davidson et al., 2005). This is especially true of the secondary $PM_{2.5}$, where atmospheric chemistry and the chemical reaction between precursor pollutants significantly depend on environmental conditions (e.g., intensity of solar radiation, temperature, humidity, and other chemical compounds present in the atmosphere) and the interactions between the gases can be nonlinear. For example, the chemical interactions between nitrogen oxides, sulfur oxides, and ammonia can lead to counterintuitive results. Reduction of sulfur dioxides (SO_2) from fuel combustion has typically lowered the concentration of sulfate (SO_4^{2-}), nevertheless might increase the level of nitrate (NO_3^-) because of the availability of ammonia (NH_3) that was

related to sulfate (SO_4^{2-}) before the reductions of sulfur dioxides (SO_2) occurred (Kelly & Fussell, 2012). Likewise, the formation of $PM_{2.5}$ from the VOCs is influenced by four components: atmospheric abundance, chemical activity, oxidizer availability, and volatility. Among the four components, volatility plays a dominant role in $PM_{2.5}$ formation. At a given temperature and pressure, organic compounds with high volatility, such as alkanes and alkenes with one to six carbon atoms vapor, is unlikely to form $PM_{2.5}$. In comparison, larger alkanes and alkenes with more than six atoms are more likely to condense into a liquid or solid, forming $PM_{2.5}$. Such examples also pose the difficulties of establishing precise and effective policies for reducing atmospheric $PM_{2.5}$ (Davidson et al., 2005).

2.3 Recent studies of contribution of on-road vehicle usage to $PM_{2.5}$

In the previous sections, a number of scientific research in the last three decades showed that on-road vehicle usage is a major source contributing to total $PM_{2.5}$ concentrations in urban areas. An increase in vehicle use on the roadway has been found to be significantly associated with a rise in $PM_{2.5}$ concentrations (Pant & Harrison, 2013). However, due to the development of cleaner technologies (e.g., three-way catalytic converters, lean NOx traps, selective catalytic reduction (SCR), and diesel particulate filters), clean air actions and stringent regulations have led to substantial declines in emissions per vehicle despite increased vehicle travel, especially in the last recent decade (Winkler et al., 2018; Harrison et al., 2021). As a result, recent studies (e.g., Harrison et al., 2021; Li & Managi, 2021) found that on-road vehicle transportation contributes to total ambient $PM_{2.5}$ less significant than the last three decades, posing an argument of whether on-road vehicle usage is still a significant source of air pollution (Amato et al., 2014; Chen et al., 2018; Grange et al., 2017; Li et al., 2017; Pant & Harrison, 2013; Yin et al., 2015).

Harrison et al. (2021) employed a machine-learning-based Random Forest algorithm and a twin site approach to estimate the contribution of road traffic to the roadside and urban concentrations of nitrogen dioxide, primary coarse particulate matter, and $PM_{2.5}$ in six major cities (i.e., London, Paris, Berlin, Beijing, Istanbul, and Hong Kong). The results reveal that on-road vehicle usage contribution to PM concentrations, especially $PM_{2.5}$, has diminished very appreciably in the studied cities. Vehicle transportation on the roadways at present represents a relatively small contribution of total $PM_{2.5}$ in urban areas; nevertheless, it remains a major source of nitrogen dioxide and a significant source of primary coarse particles. In line with the study conducted in the U.S., Li and Managi (2021) applied the spatial panel Durbin model and the geographical and temporal weighted regression to investigate the quantitative association of $PM_{2.5}$ concentrations with on-road transportation. Based on the panel data from 2001 to 2016 of 3,017 counties across the contiguous U.S., their analysis reveals that on-road transportation is no longer the dominant source of air pollution in the U.S. As the results show

that, on average, only a marginal amount around 1.09 percent of the $PM_{2.5}$ concentrations is attributable to on-road transportation. Furthermore, the study reveals that an increase of approximately 6.17 billion km per km^2 on-road transportation is associated with a 1-$\mu g/m^3$ county-level $PM_{2.5}$ concentrations increase.

2.4 Research hypothesis

Building upon the fundamental knowledge of source apportionment, physical and chemical characteristics, and the chemical formation of $PM_{2.5}$ from the atmospheric science studies, and the relevant scientific studies regarding the contribution of on-road vehicle usage to $PM_{2.5}$ concnetrations in urban areas; the research hypothesis is formulated accordingly:

Hypothesis: On-road transportation is positively related to ambient $PM_{2.5}$ concentrations in urban areas.

3. Data and Descriptive Statistics

To investigate the causal relationship between on-road transportation and $PM_{2.5}$ concentrations across cities in the United States, the analysis requires four main types of longitudinal data covering continuous sixteen time periods; years 2001 to 2016. The required four types of data include (i) a description of ambient air pollutions, specifically the average annual $PM_{2.5}$ concentrations and average annual on-road CO_2 emissions per square kilometer (km^2), (ii) a description of highway statistics, (iii) a description of sociodemographic, geographical, meteorological and economic features, and finally, (iv) a description of the 1947 planned national system of interstate highways. These acquired datasets are constructed at the Core Based Statistical Area (CBSA) level across the conterminous U.S., including Alaska and Hawaii. The CBSA is the U.S. geographic area defined by the Office of Management and Budget (OMB) that consists of the county or counties or equivalent entities associated with at least one core (urbanized area or urban cluster) of at least 10,000 population. It represents a highly populated core area and adjacent communities socioeconomically tied to the urban center by commuting. CBSAs consist of Metropolitan and Micropolitan statistical areas (U.S. Census Bureau, 2012). Apart from the four primary data, CBSA polygon geography was acquired from the 2016 Census TIGER/Line Shapefiles databases to define the core-based statistical area boundaries, map and analyze by using a Geographic Information System (GIS). Overall, there are 381 selected CBSAs in this analysis's sample.

Throughout the analysis, a dependent variable is the average annual $PM_{2.5}$ concentrations; an independent variable is the average on-road daily vehicle kilometers travelled (VKT). Apart from the main variables of interest, this study also controlled for exogenous variables that could potentially correlate with both $PM_{2.5}$ concentrations and on-road transportation; the relevant exogenous variables consist of geographical attribute (e.g., traffic congestion), sociodemographic characteristics (e.g., population density, and industrial jobs used as a proxy of industrial activities), meteorological conditions (e.g., temperature, precipitation, and wind speed), and lastly, economic factors (e.g., GDP, gasoline and diesel price, and gasoline and diesel state tax). Additionally, this thesis relied on the interaction term between the 1947 planned of the U.S. interstate highway system and fuel prices as an instrumental variable for on-road transportation. For robustness checking, the average annual on-road CO_2 emissions per km^2, and traffic intensity per CBSA are employed as the alternative measure of on-road transportation, an independent variable of this study. Besides, $PM_{2.5}$ concentration calculated at the median value is used as an alternative measure of $PM_{2.5}$ concentration per CBSA apart from the aggregate value. Detailed information regarding data employed for the robustness checking is described in section 5.3. Table A1 in Appendix A summarizes variables and data sources, while Table 3.1 below reports descriptive statistics for the main variables of interest across 381 Metropolitan areas in 51 states.

Table 3.1

Descriptive Statistic

Variable		Mean	Std. Dev.	Min	Max	Observations
$PM_{2.5}$ concentrations (satellite-derived) at an aggregate value ($\mu g/m^3$)	overall	56,728	64,309	2,333	1,445,782	N = 6,096
	between		60,130	2,871	660,288	n = 381
	within		22,999	-168,335	1,053,705	T = 16
$PM_{2.5}$ concentrations (satellite-derived) at a mean value ($\mu g/m^3$)	overall	9.01	3.12	0.79	27.40	N = 6,096
	between		2.56	1.12	14.27	n = 381
	within		1.79	4.82	31.06	T = 16
Average $PM_{2.5}$ concentrations (monitoring station-derived) ($\mu g/m^3$)	overall	10.39	3.12	2.9	51.2	N = 3,296
	between		2.36	4.23	17.93	n = 206
	within		2.05	3.85	46.25	T = 16
On-road daily VKT ('000 km)	overall	42,301	95,751	189	770,931	N = 5,240
	between		92,656	1,082	727,117	n = 376
	within		7,509	-98281	99,497	T = 13.9
Population density (people per km^2)	overall	100.67	118.83	2.43	1,026	N = 6,096
	between		118.79	2.71	1,016	n = 381
	within		6.67	38.82	168.94	T = 16
Industrial activities	overall	11,495	23,426	246	275,515	N = 5,888
	between		22,624	544	208,481	n = 381
	within		5,387	-63,344	87,558	T = 15.5
Traffic congestion	overall	10,051	3,709	363	21,756	N = 4,387
	between		3,633	374	19,998	n = 362
	within		929	4,849	18,917	T = 12.1
GDP (millions dollars)	overall	33,900	94,700	717.24	1,640,000	N = 6,096
	between		93,200	1,784.81	1,250,000	n = 381
	within		17,300	-2.69,000	4,260,000	T = 16
Precipitation (mm)	overall	80.31	35.13	1.10	267.01	N = 6,096
	between		31.64	4.18	137.18	n = 381
	within		15.34	21.39	223.85	T = 16
Temperature (°C)	overall	13.95	4.65	-5.32	25.31	N = 6,096
	between		4.52	-2.22	23.73	n = 381
	within		1.10	10.83	17.40	T = 16
Wind speed (mph)	overall	4.41	1.82	0.61	13.82	N = 6,032
	between		0.91	1.73	7.49	n = 377
	within		1.57	0.06	12.95	T = 16
Gasoline price (dollars per gallon)	overall	2.61	0.75	1.39	3.68	N = 6,096
	between		0	2.61	2.61	n = 381
	within		0.75	1.37	3.68	T = 16
Gasoline tax (dollars per gallon)	overall	0.22	0.07	0.02	0.51	N = 6,096
	between		0.06	0.08	0.35	n = 381
	within		0.04	0.02	0.48	T = 16
Diesel price (dollars per gallon)	overall	2.74	0.90	1.32	3.97	N = 6,096
	between		0	2.74	2.74	n = 381
	within		0.90	1.32	3.97	T = 16
Diesel tax (dollars per gallon)	overall	0.22	0.08	0.08	0.64	N = 6,096
	between		0.07	0.08	0.40	n = 381
	within		0.04	0.04	0.47	T = 16

3.1 Dependent variable

The average annual $PM_{2.5}$ concentrations from 2001-2016 are retrieved from NASA's Socioeconomic Data and Applications Center (SEDAC). The SEDAC is the Distributed Active Archive Centers (DAACs) in the Earth Observing System Data and Information System (EOSDIS) of the U.S. National Aeronautics and Space Administration (NASA), focusing on developing and operating systems that support the integration of earth science and socioeconomic data (SEDAC, n.d.). The retrieved 2001-2016 dataset contains average annual concentrations of ground-level fine particulate matter ($PM_{2.5}$) with dust and sea-salt filtered, measured in micrograms per cubic meter ($\mu g/m^3$) . This dataset integrates the Aerosol Optical Depth (AOD) retrievals from multiple satellite instruments, including the NASA Moderate Resolution Imaging Spectroradiometer (MODIS), Multi-angle Imaging SpectroRadiometer (MISR), and the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) (see Van Donkelaar et al., 2016). The dataset is available in the GeoTIFF raster file format with a spatial resolution of 0.01x0.01-degree (e.g., grid cells 1.1 km on a side at the equator), covering the global land surface from 70 degrees north to 55 degrees south.

To assign the concentrations of $PM_{2.5}$ data into the selected 381 CBSAs in the conterminous U.S., Alaska and Hawaii, the CBSA polygons were first overlaid on the satellite average annual $PM_{2.5}$ concentrations GeoTIFF raster. By doing so, we determine which satellite $PM_{2.5}$ grid cells overlay consolidated the CBSAs. This assignment process has done by executing a Zonal Statistics tool in the GIS software. It should be noted, however, that the CBSA polygons differ in geographical size; each CBSA polygons contain a different number of the satellite $PM_{2.5}$ grid cells, where each grid cells have different average annual $PM_{2.5}$ concentration values. Accordingly, by taking the Zonal Statistics tool, the $PM_{2.5}$ concentration value of each CBSA is calculated as an aggregate value of all satellite $PM_{2.5}$ grid cells that fall within each CBSA polygon. Appendix B illustrates this assignment process.

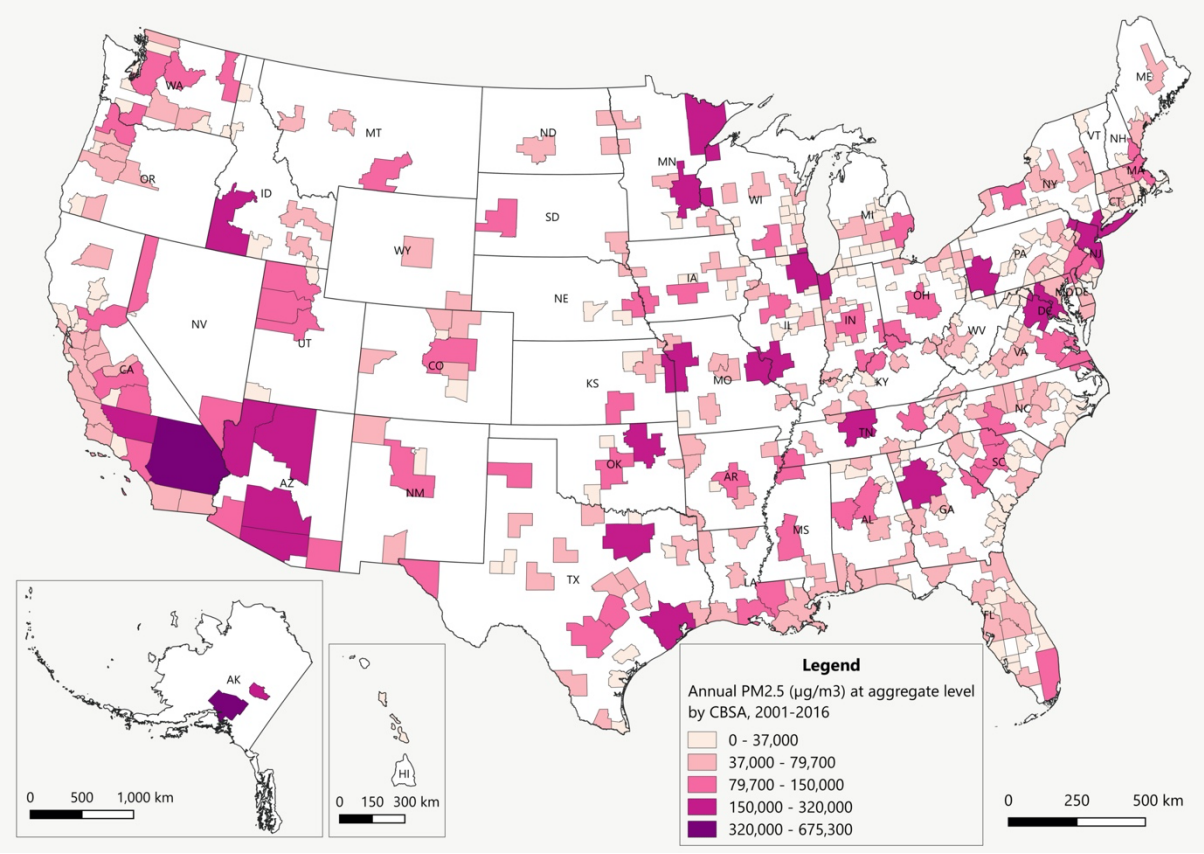
In addition, this thesis complements the primary dataset with the average annual $PM_{2.5}$ concentrations collected at the ground-level monitoring stations from the EPA Air Quality Statistics Report. This ground-level monitoring stations data is used to validate the satellite-derived data. The scatter plot demonstrating the correlation between $PM_{2.5}$ concentrations derived from ground-level monitoring stations and satellite (see Appendix C). As expected, the correlation is high, with an approximate value of 72 percent.

The first row of Table 3.1 provides descriptive statistics for the average annual $PM_{2.5}$ concentrations calculated at the aggregate value. Generally, there are 6,096 observations across 381 CBSAs over sixteen-time periods in total. The overall observations have the aggregated average annual $PM_{2.5}$ concentrations ranging from 2,333 to 1,445,782 $\mu g/m^3$, where the mean value is approximately 56,728 $\mu g/m^3$. As expected, when looking at a map of the average annual $PM_{2.5}$ concentrations calculated at the aggregate value (Figure 3.1), it is

pretty apparent that the larger CBSAs have a relatively higher aggregated average annual $PM_{2.5}$ concentrations than the smaller one. This is simply because larger CBSAs encompass a broader land area scale, including more satellite $PM_{2.5}$ grid cells that fall within their boundary, making their aggregated average annual $PM_{2.5}$ concentrations much higher.

Figure 3.1

Map of aggregated average annual $PM_{2.5}$ concentrations by CBSA over the past sixteen years from 2001-2016



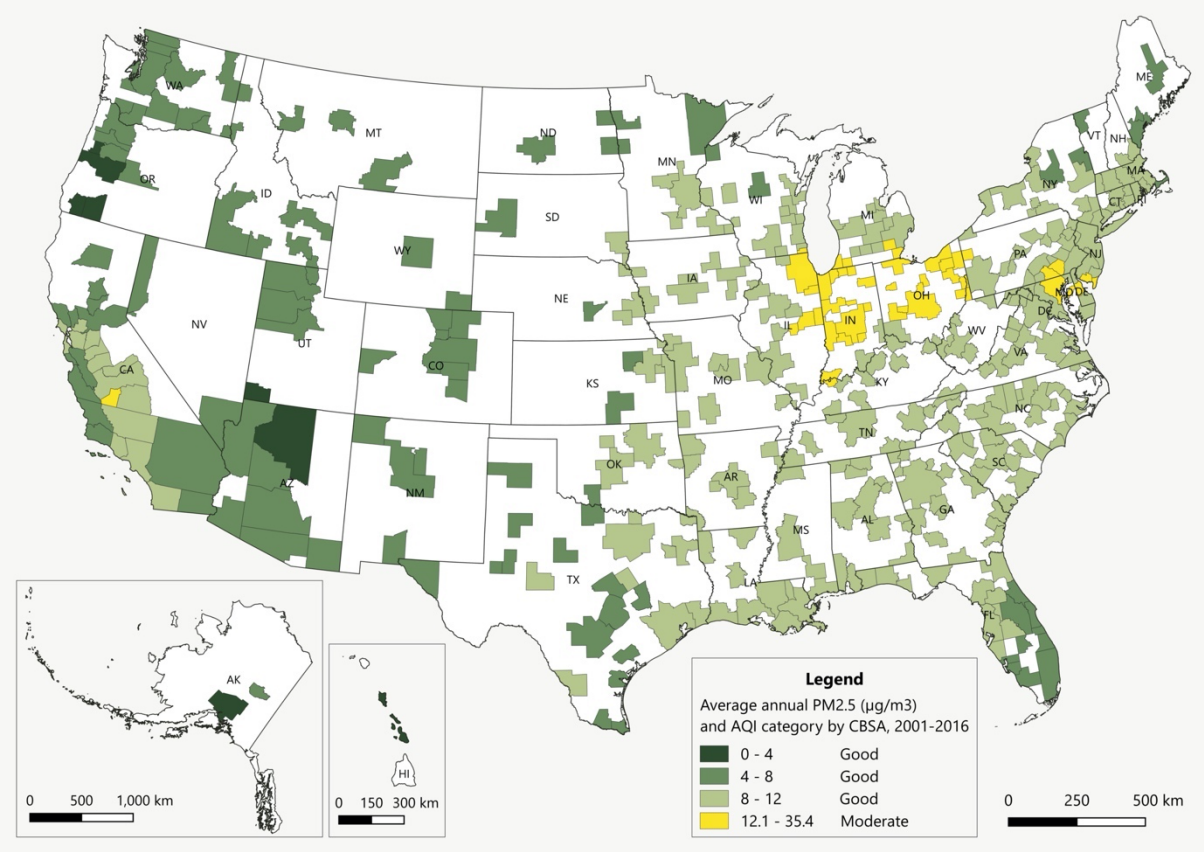
Note. White areas are non-selected-CBSA areas or non-CBSA areas, while the shaded polygons are the 381 selected CBSAs for the analysis.

However, it is interesting when considering the average annual $PM_{2.5}$ concentrations calculated at the mean value. Figure 3.2 apparently depicts that larger CBSAs do not always have higher average annual $PM_{2.5}$ concentrations than those smaller CBSAs, or vice versa. The second row of Table 3.1 provides descriptive statistics for the average annual $PM_{2.5}$ concentrations calculated at the mean value. Generally, the overall observations have the average annual $PM_{2.5}$ concentrations ranging from 0.79 to 27.40 $\mu g/m^3$, where the average value is approximately 9 $\mu g/m^3$. This mean value lands the U.S. cities in general at a "good" rating according to the U.S. Air Quality Index (AQI), which according to the stringent U.S. standards of measurement, is any concentration value between 0 to 12 $\mu g/m^3$. Interestingly, when observing the map of the average $PM_{2.5}$ concentrations over the past sixteen years

(Figure 3.2), the different levels of the average annual $PM_{2.5}$ concentration calculated at the mean value do not spatially scatter across the contiguous territory; instead, it clustered by division and state. For instance, most CBSAs with lower concentration values (0 to 8 $\mu g/m^3$) are in the Mountain division (e.g., Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, and Wyoming) and the Pacific division (e.g., Washington, Oregon, Alaska, and Hawaii). In contrast, the majority of CBSAs with a "moderate" air quality rating (i.e., concentration between 12.1 to 35.4 $\mu g/m^3$) are clustered at the East-north-central division, notably, Illinois, Indiana, and Ohio. These states moreover have recently failed to meet Environmental Protection Agency (EPA) standards for annual $PM_{2.5}$ concentrations due to significant emissions from a large number of the oil and gas refinery industry, almost 7,400 sites, particularly in Indiana (Saenz, 2019).

Figure 3.2

Map of average $PM_{2.5}$ concentrations and AQI category by CBSA over the past sixteen years from 2001-2016



Note. White areas are non-selected-CBSA areas or non-CBSA areas, while the shaded polygons are the 381 selected CBSAs for the analysis.

Lastly, consider the average annual $PM_{2.5}$ concentrations collected at the ground-level monitoring stations. The third row of descriptive statistics Table 3.1 shows that ground-level monitoring station-derived concentrations are relatively higher than the satellite-derived

data, suggesting that ground-level monitoring stations may be located in more polluted areas. Therefore, using the ground-level monitoring station-derived concentrations may be labeled endogenous errors of measurement.

3.2 Independent variable

On-road vehicle kilometers travelled (VKT) is employed as a primary measure of on-road transportation. It measures the total mileage for all on-road vehicles driven in a geographic area over a particular time, generally in an annual period. VKT is calculated by totaling up the number of kilometers traveled by all on-road vehicles (e.g., light-duty vehicles, motorcycles, trucks, and busses), including both personal and commercial travel on all roadways within a region (Williams et al., 2016). In addition, VKT is also a fundamental metric executed extensively in transportation planning to perform various functions, such as an allocation of resources, estimation of vehicle-related emissions, computation of energy consumptions, and evaluation of traffic effects (Kumapley & Fricker, 1996).

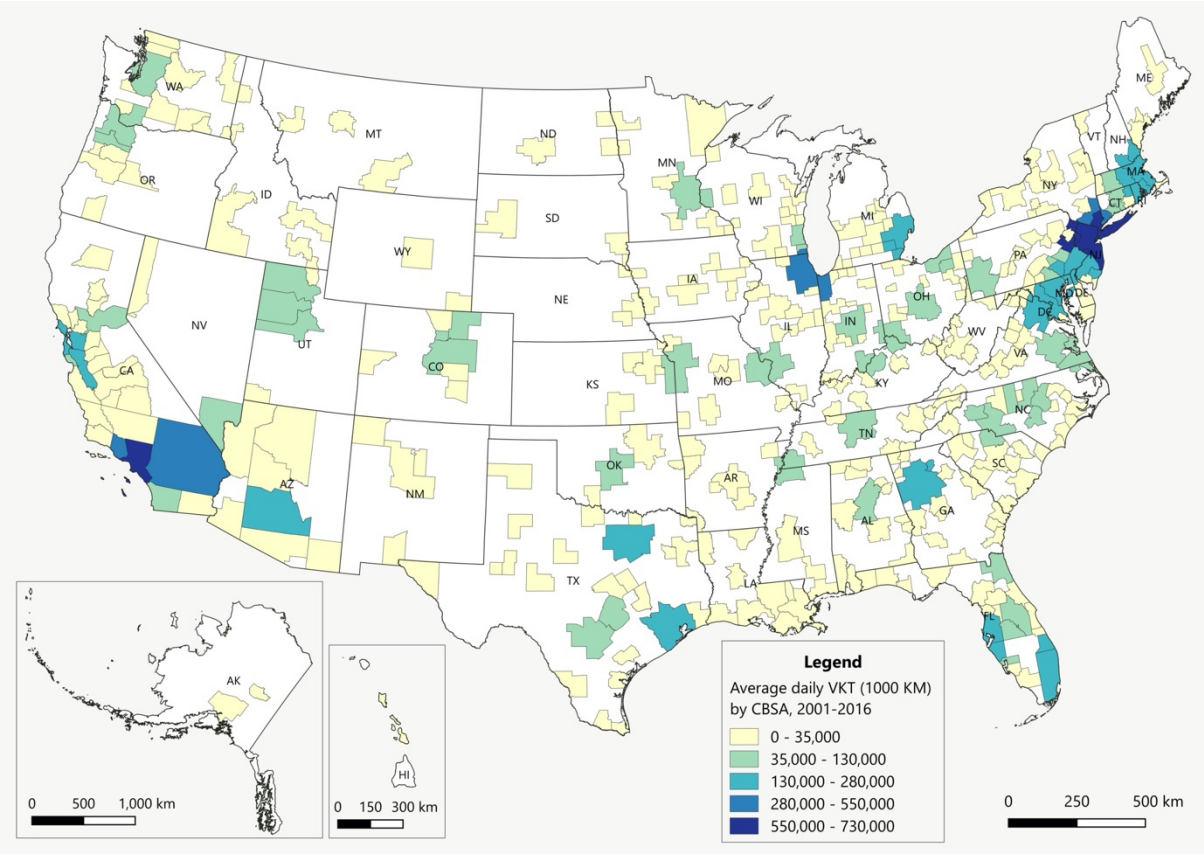
Data on the on-road daily VKT are retrieved from the annual Highway Statistics report provided by the U.S. Federal Highway Administration (FHWA). However, there are only fifteen years of observations obtained in total (i.e., between 2001-2008 and 2010-2016) because the data in the year 2009 are not available in the annual Highway Statistics series. Besides, the FHWA reports their statistics data in the level of "urbanized areas" where the term "urban" used in the report is defined as "areas include, at a minimum, a census place with an urban population of 5,000 to 49,999 or a designated urbanized area with a population of 50,000 or more" (FHWA, 2014). Since this study constructs the observation unit at the CBSA level.[2] Each CBSA typically aggregates county or counties associated with one or more urbanized areas. By using VKT data collected at the level of "urbanized areas", this study, therefore, consolidates "urbanized areas" in the same CBSA together and calculates the on-road daily VKT per each CBSA at the aggregate value. It should be noted, nevertheless, that CBSA boundaries often encompass much land that is not "urban" in the ordinary sense of the word. This fact, indeed, could lead to an argument of a measurement error. That is, on-road daily VKT derived from totaling up VKT data at the "urbanized areas" level does not seem to entirely represent an actual VKT of each CBSA, which also includes VKT from the non-urbanized areas. However, according to the FHWA Highway Statistics (2016), almost 80 percent of total on-road VKT is in urbanized areas. Thereby, we expect that using VKT data collected only from urbanized areas will not pose a significant bias in the estimation, especially when the main interest of this paper is to investigate the relationship between $PM_{2.5}$

[2] This study constructs the unit of observation at the level of "CBSA" instead of "urbanized area" because the "urbanized area" level is relatively small in size. This could potentially lead to a measurement error, particularly when measuring the level of $PM_{2.5}$ concentrations, as $PM_{2.5}$ can easily diffuse across the adjacent areas. Furthermore, most of the relevant variables required in this study's analysis are provided at the CBSA level.

concentrations and driving in the city boundary. As a consequence, the first assumption was made that on-road daily VKT derived from the aggregate of VKT data at the "urbanized areas" level represents an on-road daily VKT of a given CBSA.[3]

Figure 3.3

Map of average daily on-road Vehicle Kilometers Travelled (VKT) by CBSA from 2001-2016



Note. White areas are non-selected-CBSA areas or non-CBSA areas, while the shaded polygons are the 381 selected CBSAs for the analysis.

The fourth row of Table 3.1 reports descriptive statistics for the on-road daily VKT. The overall number of observations is lower than the average annual $PM_{2.5}$ concentrations and other variables due to the unavailability of the 2009 data and some missing values. The average mileage driven per day by the U.S. cities is approximately 42,301,000 km. When observing the map of the average daily on-road VKT by CBSA over 2001-2016 (Figure 3.3), like the aggregated average annual $PM_{2.5}$ concentrations map (Figure 3.1), an average daily on-road VKT is scattered across the U.S. territory where the larger CBSAs tend to have a higher level of on-road daily VKT than the smaller CBSAs, and vice versa. Naïve comparison thus suggests a positive correlation between the aggregated $PM_{2.5}$ concentrations and driving.

[3] The first assumption was made that way because the data of on-road daily VKT are not available at the CBSA level. Alternatives are available at the state and national level, however, they does not applicable to this study's unit of observations.

3.3 Control variables

Besides the main variables of interest, several exogenous variables that could potentially correlate with both $PM_{2.5}$ concentrations and on-road transportation are controlled in some econometric models. Such exogenous variables are geographical attribute (e.g., traffic congestion), sociodemographic characteristics (e.g., population density, and industrial jobs used as a proxy of industrial activities), meteorological conditions (e.g., temperature, precipitation, and wind speed), and lastly, economic factors (e.g., GDP, gasoline and diesel price, and gasoline and diesel state tax). The validity of these exogenous variables is described in detail in the following sections.

Geographical attribute

To begin with geographical attribute, traffic congestion is a condition in transport often defined as periods when traffic volume exceeds road capacity, typically caused by high traffic volumes. It is characterized by slower speeds that negatively impact the transportation system by increasing travel times, travel costs, and air pollution (Zhang & Batterman, 2013; Sardari et al., 2018). According to Zhang and Batterman (2013), high traffic volumes or traffic congestion lowers the average speed, which increases travel time, thus directly increasing tailpipes emissions. Furthermore, traffic congestion can alter driving patterns. Driving under "congestion" conditions leads to an increased number of speedups, slowdowns, stops, and starts, which increases tailpipes emissions compared to "cruise" conditions, particularly with high power acceleration. In addition to impacts on ambient air pollution, adverse outcomes caused by traffic congestion have been found to affect commuters' travel behavior. According to Ben-Akiva et al. (1985), commuters change their travel behaviors to maximize utility and save time by avoiding traffic congestion. Such results in lower demand for travel, therefore, lower VKT. To measure traffic congestion, data on Annual Average Daily Traffic (AADT) acquired from the U.S. FHWA are employed as a proxy of traffic congestion. AADT is a fundamental traffic element to many transportation performance and planning measures. It indicates vehicle traffic volume on a road segment and measures how busy a road is (FHWA, 2018). Traditionally, AADT estimates the mean traffic volume across all days for a year for a given location along a roadway, computed by dividing the sum of total traffic for the entire year by 365 days. However, the retrieved AADT data from the FHWA are computed using the FHWA AADT method to reduce bias (see FHWA, 2018, P.6).

Sociodemographic characteristics

Population densities, also typically referred to as the economic density, are the number of economics agents living or working within a spatial unit (Burton, 2002; Neuman, 2005). The population density characteristics have been widely found to substantially influence the concentrations of air pollutions (Ewing & Cervero, 2010; Frank et al., 2008; Nam et al., 2012; Stone, 2008; Stone et al., 2007), and a reflector of transportation demand in cities (Lai et al.,

2000). According to the studies, cities with low population densities are often characterized by sprawling development patterns with low mixed-use, scattered, and highly segregated land uses and economic activities. These combined characteristics encourage vehicle dependency and increase trip length, VKT, and fuel consumption, consequently raising tailpipes emissions. Conversely, high population density cities are typically characterized by high mixed-use and high density of the built environment (Ahfeldt & Pietrostefani, 2017). This urban development pattern is associated with a shorter trip length, resulting in less automobile use and VKT (Bechle et al., 2011). However, the traffic concentration in dense areas can lead to a high concentration of emissions (Troy 1996), while taller buildings in high dense cities tend to emit fewer pollution particles but could also trap pollution known as a "street canyon" (Ahfeldt & Pietrostefani, 2017). Data on population density are the GeoTIFF raster file provided by the University of Southampton from 2001 to 2016 with a 100-m resolution and estimated via unconstrained top-down methods (see Lloyd et al., 2019). The assignment process of population density to each CBSA has been performed as with $PM_{2.5}$ concentration data (Appendix B).

According to Karagulian et al. (2015), industrial activities are one of the primary pollution sources contributing to total $PM_{2.5}$. Globally, industrial activities contribute approximately 15 percent, while it contributes around 9 percent to the total $PM_{2.5}$ in the U.S. cities. Apart from being a significant source of air pollution, industrial activities also directly influence travel demand through transportation of raw materials and freight, and as well as commuting of workers and laborers. Consequently, having a greater amount of industrial activities is likely to associate with higher VKT. To quantify the number of industrial activities, the total number of jobs hired in the industrial sectors is used to proxy industrial activities. Industrial employment information is obtained from the U.S. Census Bureau's Longitudinal Employer-Household Dynamics (LEHD). The LEHD categorized a range of employment types using the North American Industry Classification System (NAICS). According to the NAICS, the total number of industrial employment is the sum of jobs in agriculture, forestry, fishing and hunting, mining, quarrying, oil and gas extraction, utilities, construction, manufacturing, wholesale trade, and transportation and warehousing.

Meteorological conditions

Temperature, precipitation, and wind speed are the three influential meteorological conditions affecting the diffusion, dilution, and accumulation of $PM_{2.5}$ concentrations (Liang & Gong, 2020; Wang & Ogawa, 2015). Temperature affects $PM_{2.5}$ through photochemical reactions of $PM_{2.5}$ precursor pollutants in the atmosphere. As described in detail in the theoretical framework section, $PM_{2.5}$ pollution generally arises from a direct emission from pollution sources and from a formation of gaseous precursor emissions in the atmosphere through the gas-to-particle conversion process. Sunlight and high-temperature increase the

rate of photochemical reactions of sulfur dioxides (SO_2), nitrogen oxides (NO_x) and VOCs to a formation of $PM_{2.5}$ precursor pollutants (Wang & Ogawa, 2015). Consequently, the hotter the day and the more intense the sun, the more $PM_{2.5}$ are formed from its precursor pollutants.

Unlike temperature conditions, precipitation and wind speed have been found to significantly negatively correlate with the concentration of $PM_{2.5}$ (Hernandez et al., 2017; Liu et a;., 2020; Wang & Ogawa, 2015). Precipitation has a wet scavenging effect on aerosol particles. It affects the natural deposition process of particulate matter. The low relative humidity is conducive to the adhesion of atmospheric particulate matters on moisture particles, leading to more accumulation of $PM_{2.5}$ concentrations in the atmosphere. At the same time, relatively high humidity leads to a growth in the size of moisture particles to the point of "dry deposition" that lowers $PM_{2.5}$ concentrations in the atmosphere by rainfall (Wang & Ogawa, 2015). For wind speed, it could transport emissions from the pollution sources to the adjacent areas. However, light winds cause emissions to build up above ground level (Wang & Ogawa, 2015).

In addition, extreme meteorological conditions trigger more energy consumption in buildings and automobiles, which emits more air pollution. Moreover, it also affects travel behavior; dwellers are more likely to switch from active transport modes (e.g., walking and cycling) to automobile dependency on hot, cold, snowy and rainy days, causing more VKT. Information on meteorological features is obtained from WorldClim global climate and weather data website (see Fick & Hijmans, 2017). The retrieved data are also available in the GeoTIFF raster file with a very high spatial resolution of about 1 km^2. The assignment process of meteorological features to each CBSA has been performed as with $PM_{2.5}$ concentration data.

Economic factors

Fuel prices, both gasoline and diesel, directly affect driving behavior in terms of transportation costs. Rising fuel prices can be seen in declining fuel consumption, roadway traffic volumes and VKT, and shifting commuters' choice of transport modes to respond to higher transportation costs (Austin, 2008). According to the Congressional Budget Office (CBO) research, people are less responsive to the changes in fuel prices in the short run than in the long run. In the short run, a 10 percent increase in the retail price of fuel decreases consumption by about 0.6 percent and VKT by as little as 0.2 to 0.3 percent; at the same time, fuel consumption and VKT decline much larger, in the long run, roughly 4 and 1.5 percent, respectively (Austin, 2008). In addition, volatile petroleum prices typically affect the expected rate of economic growth through their effect on supply and demand for goods, the firm's productivity, energy consumption to produce goods, and consequently emissions (Blanchard & Gali, 2007; European Central Bank, 2004). Likewise, taxes on fuel increase transportation costs and productivity costs, leading to lower VKT and emission (Chen & Lin, 2015).

Gross domestic product (GDP) is a useful indicator of economic activity. The relationship between economic growth, VKT, and air pollution has long been observed to be significantly correlated but in a dynamic way (Luo et al., 2014; Liddle, 2009; Pozdena, 2009). One aspect of a rising GDP is that it indicates employment growth, resulting in a higher commuter's travel demand. Rising GDP also implies higher productivity, which correlates with increased production capacity, raw material, and freight transportation. All of which raise VKT. At the same time, rising GDP due to the concentration of manufacturing industries activities can deteriorate air quality from a more emission of higher productivity (Liang & Gong, 2020).

Lastly, data on yearly gasoline and diesel prices and yearly gasoline and diesel state taxes are acquired from the U.S. Energy Information Administration (EIA). In contrast, data on the annual GDP per each CBSA are obtained from the U.S. Bureau of Economic Analysis (BEA).

3.4 Instrumental variables

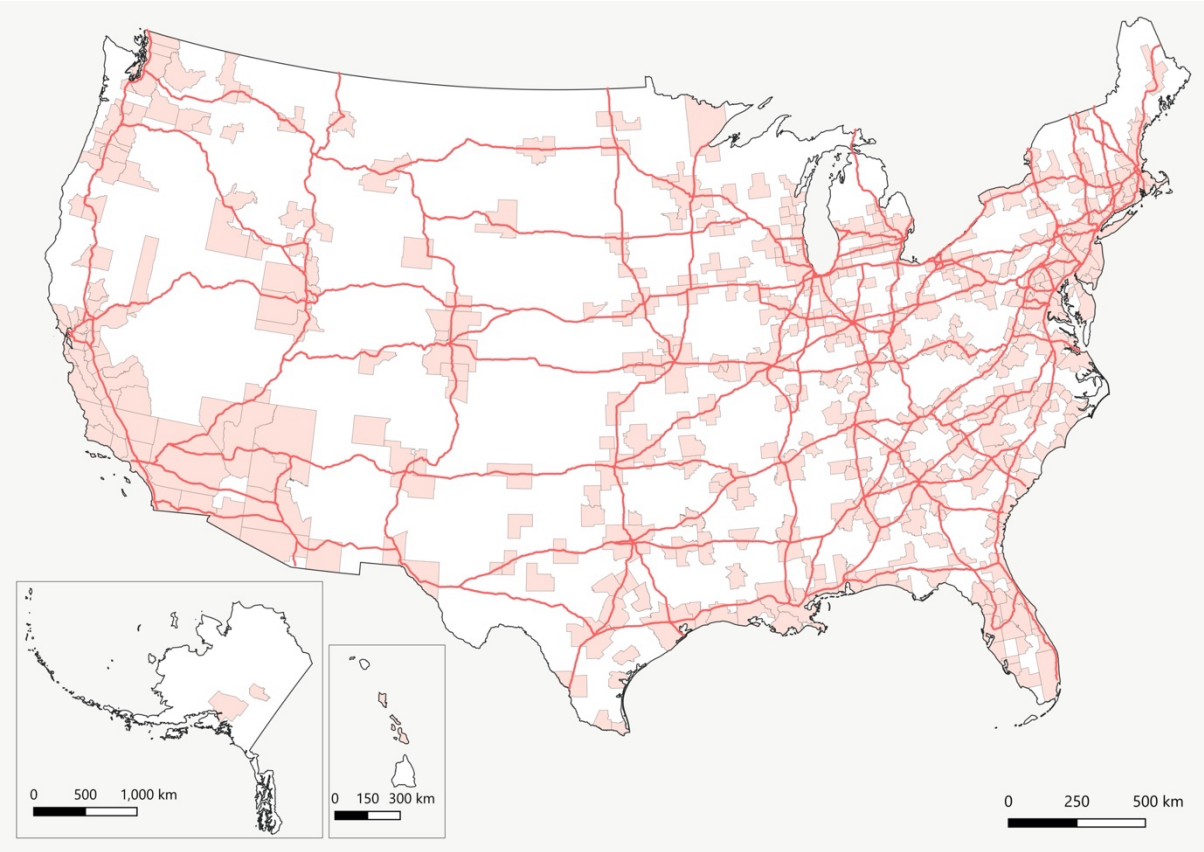
In the instrumental variables estimation, this paper relies on *the interaction term between the 1947 planned national system of interstate highways and fuel prices* as an instrumental for driving. The interstate highways system was first described in a Bureau of Public Roads report to Congress, Toll Roads and Free Roads, in 1939. It was authorized for designation by the Federal-Aid Highway Act of 1944, with the initial designations in 1947, planned to construct a 40,000 miles (or approximately 64,000 km) interstate highway system (Weiner, 1997). This interstate highways system plan considered a strategic highway network proposed by the War Department, the location of military establishments, interregional traffic demand, and the distribution of population and economic activity at that time. By 1980, the federal interstate highway system was substantially complete (Duranton & Turner, 2012).

To measure kilometers of the 1947 planned national system of interstate highways in each CBSA, this study first constructed a digital map of the 1947 interstate highway plan. This process has been done by converting an image of the original plan retrieved from its paper record (United States House of Representatives, 1947) to a digital map as performed in Duranton and Turner (2012). After that, Kilometers of 1947 planned interstate highways in each CBSA are calculated directly from this digital map. Figure 3.4 depicts an digital map of the 1947 planned national system of interstate highways over the selected 381 CBSAs, while an image of the original plan can be found in Figure D1, Appendix D.

Across the selected 381 CBSAs, the 1947 national system of interstate highways was planned to construct through 292 CBSAs. The mean kilometers of the 1947 interstate highways plan per the selected CBSAs is roughly 95 km. Validity of the 1947 planned national system of interstate highway and its interaction term with fuel prices instrument is discussed in detail in the methodology section.

Figure 3.4

Digital map of 1947 planned National System of Interstate Highways



Note. The red lines are the 1947 planned interstate highways. The light pink shaded polygons are the selected CBSAs in the study sample. Data source: Map based on United States House of Representatives (1947).

4. Methodology

The objective of this thesis is to investigate the causal relationship between on-road transportation and $PM_{2.5}$ concentrations across U.S. cities. Accordingly, this study begins by testing the proposed hypothesis of whether on-road transportation is positively related to the concentrations of $PM_{2.5}$ in urban areas, employing the ordinary least squares (OLS) models. However, endogeneity problem often arises from using the OLS estimations, potentially causing the risk of biased and inconsistency for the OLS estimator (Bun & Harrison, 2019). Consequently, the instrumental variables (IV) estimation, a common technique for obtaining a consistent estimator of the coefficient of interest, is then performed to address the endogeneity problems. The detailed methodologies to test the research's hypothesis are described in the following section.

4.1 OLS estimations

The OLS estimations are firstly employed for this empirical analysis to investigate the causal effect of driving on $PM_{2.5}$ concentrations. Throughout the OLS models, a dependent variable is the average annual satellite-derived $PM_{2.5}$ concentrations, an independent variable is on-road daily vehicle kilometers travelled (VKT). Apart from the main variables of interest, eleven exogenous variables as suggested by theoretical and empirical literature to correlate to the level of ambient air pollutions and on-road vehicle usage described in detail in section 3.3 are included in some OLS models to limit any potential endogeneity problem.

In order to obtain the possible BLUE (Best Linear Unbiased Estimator) of the OLS estimator, the data and regression models are required to satisfy all of the standard Gauss Markov assumptions. Firstly, several variables are transformed into the logarithmic functional form to meet linearity in parameters assumption and to achieve approximate homoscedasticity by removing a systematic change in the spread of the residuals over the range of measured values. By taking a logarithmic transformation, furthermore allows direct comparison between elasticities (Wooldridge, 2015). Secondly, no perfect collinearity means that none of the independent variables is constant and there are no exact linear relationships among the independent variables (Wooldridge, 2015). Another concern about collinearity is multicollinearity which refers to a highly (but not perfect) correlation between multiple independent variables. Although the problem of multicollinearity cannot be clearly defined, for estimating the parameters, it is better to have less correlation between each independent variable (Wooldridge, 2015). The rule of thumb is that severe multicollinearity may be present if the correlation between independent variables > 0.8 in absolute value. Appendix E reports the Pairwise correlation coefficient among independent variables to clarify the collinearity. According to the Pairwise correlation coefficient reports, only the correlation between industrial activities and GDP, and the correlation between gasoline and diesel prices happens to have a higher correlation coefficient exceeding the rule of thumb.

Lastly, the zero conditional mean assumption indicates no correlation between the independent variable (x) and the error term (ε), or in other words, the error term has an expected value of zero given any value of the explanatory variable, $E(\varepsilon|x) = 0$. This assumption is also referred to as *exogeneity*. Conversely, a situation in which an independent variable is correlated with the error term or $E(\varepsilon|x) \neq 0$, is referred to as *endogeneity* leading to a violation of the zero conditional mean assumption and causing the OLS estimator biased and inconsistent. Endogeneity arises from unobserved or omitted variable bias, measurement error in the independent variable, and simultaneity bias (Wooldridge, 2015).

This study utilized time fixed effect and entity fixed effect (e.g., a fixed effect at the CBSA and state level) in the regression models to limit estimation biases, particularly from unobserved variables. By combining both fixed effects allows eliminating bias from unobserved or omitted factors that vary across the CBSAs and states but are constant over time (entity fixed effect) and allows to control for unobserved or omitted variables that vary over time but are constant across the CBSAs and states (time fixed effect) (Wooldridge, 2015). Some examples of variables that are unobservable or difficult to measure and strongly influence ambient air pollution and driving but could be addressed by using the fixed effects are land-use planning policies and related rules and programs implemented to reduce fine particle pollution emissions. According to Burchell and Lahr (2008), each cities' and state's institutional structure for land-use policies decision-making is different. For instance, cities and local governments autonomously control their land-use policies in states like Maryland, Virginia, New England states, and other East Coast states. In contrast, state authorities and regional governments have much control over land-use planning policies in most Midwest, Rocky Mountain, and West Coast states. In addition, different rules, policies, and programs aimed to reduce fine particle pollution emissions have been implemented differently across the states (EPA, n.d.). For example, California's cap-and-trade program, the cap-and-invest implemented in Washington, and the Illinois Climate Action Plan (iCAP). These different programs and policies could effect on-road vehicle usage and emissions vary across the states.

Putting together, thereby, the OLS estimation model is as follows:

$$\begin{aligned} ln\,(PM_{2.5}\ concentrations_{it}) = {} & \beta_0 + \beta_1\, ln\,(on\text{-}road\ daily\ VKT_{it}) + \gamma_1\, ln\,(traffic\ congestion_{it}) \\ & + \gamma_2\, ln\,(population\ density_{it}) + \gamma_3\, ln\,(industrial\ activities_{it}) \\ & + \gamma_4\, ln\,(temperature_{it}) + \gamma_5\, ln\,(precipitation_{it}) \\ & + \gamma_6\, ln\,(wind\ speed_{it}) + \gamma_7\, ln\,(GDP_{it}) + \gamma_8\, ln\,(gasoline\ prices_{it}) \\ & + \gamma_9\, ln\,(diesel\ prices_{it}) + \gamma_{10}\, ln\,(gasoline\ taxes_{it}) \\ & + \gamma_{11}\, ln\,(diesel\ taxes_{it}) + \alpha_c + \lambda_{ts} + \varepsilon_{it} \end{aligned} \quad (1)$$

where i indexes CBSAs, t indexes time periods. β_0 is the intercept, β_1 is the parameter of interest measuring the effect of on-road daily VKT on the $PM_{2.5}$ concentrations. γ_1 to γ_{11} are the estimated regression coefficients that quantify the association between the exogenous variables and the $PM_{2.5}$ concentrations. α_c is the CBSA fixed effect, λ_{ts} is the interaction term between time and state fixed effects, and ε_{it} is the error term.

A causal interpretation of the coefficient of interest requires variation in on-road daily VKT to be exogeneous to other factors of $PM_{2.5}$ concentrations. On-road daily VKT is influenced by a whole raft of factors. Some of the factors could well directly cause ambient air pollutions. While including both time and state fixed effects to control for other determinants of ambient air pollutions may help solve endogeneity problems, these fixed effects cannot control for characteristics that vary across the CBSAs, states and change over time, which can still be a source of omitted variables bias. As a consequence, this study resolves this problem by relying on instrumental variables estimations.

4.2 IV estimations

Instrumental variables regression is a technique for acquiring a consistent estimator of the coefficient of interest (Wooldridge, 2015). This study exploit the interaction term between the 1947 planned of the U.S. interstate highway system and fuel prices as an instrumental variable for driving to resolve endogeneity. To see how the IV estimation addressing the endogeneity problem, this study consider the system of equations:

$$y_{it} = \theta_0 + \beta x_{it} + \delta_{it} \tag{2}$$

$$x_{it} = \pi_0 + \pi_1 z_{it} + \eta_{it} \tag{3}$$

In the context for this equations system, given that y_{it} denotes $PM_{2.5}$ concentrations, x_{it} indexes on-road daily VKT, and z_{it} is the interaction term between 1974 interstate highway plan and fuel prices instrument. Endogeneity problem arises when the on-road daily VKT is correlated with the error term or $E(\delta_{it} \mid x_{it}) \neq 0$. This bias can be resolved by exploiting instrumental variables estimations. According to the system of equations, it will be identified only if the interaction term between the 1974 interstate highway plan and fuel prices instrument satisfies two conditions. Firstly is a relevance condition that requires that, conditional on control variables, interaction term between the 1974 interstate highway plan and fuel prices instrument predicts the on-road daily VKT, or $\pi_1 \neq 0$. Secondly is exogeneity condition or exclusion restriction. This condition requires that interaction term between the 1974 interstate highway plan and fuel prices instrument affect $PM_{2.5}$ concentrations only through their effect on on-road daily VKT, or $E(z_{it} \mid \delta_{it}) = 0$.

Regarding the relevance condition, evidence from empirical and historical research suggests that the instrument should be relevant as it predicts the on-road daily VKT. According to Duranton and Turner (2011), the 1947 plan of the U.S. interstate highway system was subsequently constructed and substantially complete by the 1980s. This plan, therefore, represents most of the highways system operating today. In addition, Duranton and Turner observe that the assignment of highways to CBSAs according to the 1974 plan results in more roadway in the present. Cities that received more roadways in the 1947 plan tend to have greater roadway kilometers than cities that received fewer. Furthermore, their finding reveals that on-road VKT increases proportionately to roadway kilometers. Consequently, using the 1947 plan of the U.S. interstate highway system as an instrument for on-road daily VKT should satisfy the relevance condition.

Concerning the exogeneity condition, common sense suggests that the 1974 interstate highway plan should not directly affect the level of $PM_{2.5}$ concentrations unless only through their effect on the on-road daily VKT. The 1947 plan was first drawn to "*connect by routes as direct as practicable the principal metropolitan areas, cities and industrial centres, to serve the national defense and to connect suitable border points with routes of continental importance in the Dominion of Canada and the Republic of Mexico*" (U.S. Federal Works Agency, 1947, cited in Michaels, 2008). According to the mandate, the 1947 highway plan makes no mention of environmental related-issues. Thereby, it can be concluded that the 1947 highway plan was drawn, as stipulated by its mandate, to connect major metropolitan areas and to serve national defense as of the mid-1940s. To sum up, the 1947 highway plan predicts the current roadway kilometers but should not predict future environmental issues, particularly air pollution.

It is noted that employing the interaction term between the 1974 interstate highway plan and fuel prices as an instrument will leverage the time-variant impacts of the roadway kilometers.

Formally, the IV estimates for examining the impact of on-road daily VKT on $PM_{2.5}$ concentrations obtained following the standard two stage least squares procedure (2SLS) are accordingly:

$$ln\,(\widehat{on\text{-}road\ daily\ VKT}_{it}) = \beta_0 + \delta\ interaction\ term\ between\ highway\ plan\ and\ fuel\ prices_{it} + \gamma' X_{it} + \alpha_c + \lambda_{ts} + \varepsilon_{it} \quad (4)$$

$$ln\,(PM_{2.5}\ concentrations_{it}) = \beta_0 + \omega\, ln\,(\widehat{on\text{-}road\ daily\ VKT}_{it}) + \gamma' X_{it} + \alpha_c + \lambda_{ts} + \varepsilon_{it} \quad (5)$$

Equation (4) is the first-stage regression, i indexes CBSAs, t indexes time periods. β_0 is the intercept, δ is the coefficients measuring the effect of instrumental variable on on-road daily VKT. Vector X_{it} corresponds to vector of control variables, as outlined in equation (1) excluding gasoline and diesel prices, and γ' is a conformable vector of coefficients. α_c is the

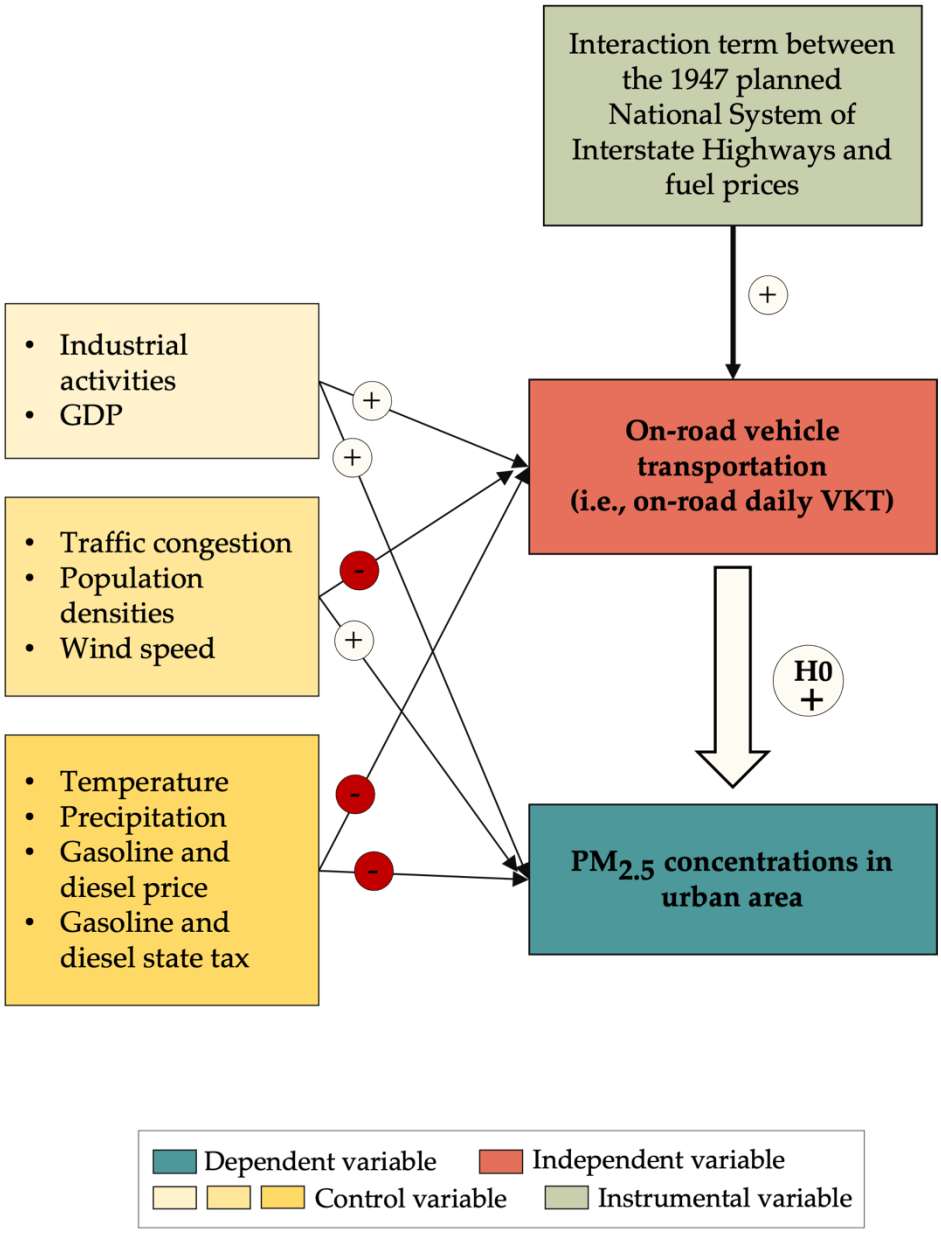
CBSA fixed effect, λ_{ts} is the interaction term between time and state fixed effects, and ε_{it} is the error term. Equation (5) is the second-stage regression, ω is the 2SLS estimator indicating the effect of on-road daily VKT on $PM_{2.5}$ concentrations.

4.3 Conceptual model

Based on the theoretical framework, data, and methodology sections, the model tested in this study is schematic as follows:

Figure 4.1

Schematic conceptual model



5. Results

This results section proceeds in three steps. First, results from the OLS estimations showing the relationship between $PM_{2.5}$ concentration and the preferred measures of driving, i.e., on-road daily VKT, are presented, followed by results from the instrumental variable estimations employed to resolve the endogeneity problem. Finally, this thesis verifies that these relationships are robust to different $PM_{2.5}$ concentrations and driving measures by presenting the results from both the OLS and IV estimations depicting the relationship between $PM_{2.5}$ concentration measured at the median value and the alternative measures of driving, i.e., traffic intensity and aggregated CO_2 emissions from the on-road transportation sector.

5.1 OLS estimations

This study first estimates structural Equation (1) by OLS. These baseline OLS estimations only provide valid estimates of the econometric model if unobserved factors of on-road daily VKT are uncorrelated with unobserved factors of the level of $PM_{2.5}$ concentrations. As described in detail in section 4.1, this condition presumably fails to hold; consequently, the following results estimated by OLS should be regarded as primarily descriptive.

Columns 1, 2, 3, and 4 of panel A in Table 5.1 report the results of OLS estimations of driving on ambient air pollution. The dependent variable is the natural logarithm of $PM_{2.5}$ concentrations computed at the aggregate value in every column, and the measure of driving is the natural logarithm of on-road daily VKT in all specifications. The unit of observation is the CBSA.

To begin with column 1, this study regresses the natural logarithm of aggregated $PM_{2.5}$ concentrations on the natural logarithm of on-road daily VKT to find an elasticity of 16.7%, statistically significant at the one percent level. This suggests that a 1% increase in on-road daily VKT would result in an approximately 0.17% increase in the aggregate level of $PM_{2.5}$ concentrations. At the sample mean, this represents that every 423,010 kilometers increase in daily vehicle mileage is associated with 94.74 $\mu g/m^3$ increases in the aggregate level of $PM_{2.5}$ concentrations. As expected, the effect of on-road vehicle use on $PM_{2.5}$ concentrations is marginal, which is in line with the finding by Li and Managi (2021). In column 2, a full set of control variables (i.e., geographical, sociodemographic, meteorological, and economic factors) are added to the specification in column 1 and estimate an adverse effect of on-road daily VKT on $PM_{2.5}$ concentrations, with an elasticity of -1.3%, statistically significant at the five percent level. Contradictorily to column 1, this negative elasticity implies that a 1% increase in on-road daily VKT would decrease the aggregate level of $PM_{2.5}$ concentrations by about 0.01%. The differences between the two elasticities assumably due to a loss of observations, dropped

from 5,240 to 4,150, accounting for about 21%, when including control variables. Another reason is probably due to the collinearity of on-road daily VKT and some control variables such as population density, industrial activities, and GDP.

In column 3, this study returns to the specification of column 2 but also includes the entity fixed effect at the CBSA level. Estimating the elasticity of aggregate $PM_{2.5}$ concentrations with respect to on-road daily VKT yields a coefficient much smaller in magnitude relative to column 2 but not statistically significant at the one or five percent level. Consistent with this, including both CBSA fixed effect and the interaction term between state and time fixed effects in column 4 also provides a negative coefficient on on-road daily VKT which is slightly different from that of column 3, from the elasticity of -0.8% to -0.4%, however, the coefficient is also not statistically significant. Among the four baselines OLS regressions, the preferred specification is column 4, where a full set of the control variables, CBSA fixed effect, interaction term between time fixed effect and state fixed effect are included in the estimating equation.

In spite of differences across specifications, the OLS elasticity of the aggregate $PM_{2.5}$ concentrations relative to on-road daily VKT remains small, ranging between -1.3% and 16.7%. If we restrict attention to the preferred specification, column 4, then on-road transportation does not significantly affect the aggregated concentrations of $PM_{2.5}$.

5.2 IV estimations

Column 5, 6 and 7 in Table 5.1 reports the results of instrumental variable estimations. Before proceeding to the main IV results, this study first provides estimates of the first-stage regression reported in panel (B). This results from estimating equation (4), in which in column 5, the natural logarithm of on-road daily VKT is regressed on the interaction term between the 1947 interstate highways plan and fuel prices instrument. In column 6, a full set of control variables (i.e., geographical, sociodemographic, meteorological, and economic factors) are added to the specification in column 5. Lastly, in column 7, a complete set of control variables as well as fixed effects are additionally added to the specification in column 5.

Regarding the relevance condition, in all specifications, the Kleibergen-Paap rk Wald F-statistics tests on the interaction term between the 1947 interstate highways plan and fuel prices coefficient of column 5, 6 and 7 are 1,276, 33.74 and 17.52, respectively. The Kleibergen-Paap rk Wald F-statistics tests of the three IV models exceed the rule of thumb, 10. This has two important implications; (i) it indicates that the instrument is not weak, and (ii) the relevance condition is satisfied. Concerning the effect of the interaction term between the 1947 interstate highways plan and fuel prices instrument on on-road daily VKT, as expected, the coefficient is positive, suggesting that the interaction term between the 1947 interstate highways plan and fuel prices instrument positively predicts VKT on the roadways, in line with the finding by Duranton and Turner (2011).

Table 5.1

On-road daily VKT and aggregated $PM_{2.5}$ concentrations

(A) Main result	(1) OLS	(2) OLS	(3) OLS, FE	(4) OLS, FE	(5) IV	(6) IV	(7) IV, FE
Ln(On-road daily VKT)	0.167***	-0.013**	-0.008	-0.004	0.634***	0.685***	0.237
	(0.009)	(0.007)	(0.014)	(0.007)	(0.014)	(0.118)	(0.150)
Ln(Population density)		-0.795***	0.161**	0.047		-1.133***	-0.230
		(0.009)	(0.065)	(0.038)		(0.063)	(0.174)
Ln(Industrial activities)		0.310***	0.179***	-0.022**		0.343***	-0.032**
		(0.015)	(0.017)	(0.011)		(0.026)	(0.013)
Ln(Traffic congestion)		0.011	0.045*	-0.001		-0.517***	-0.067
		(0.016)	(0.025)	(0.012)		(0.095)	(0.045)
Ln(GDP)		0.522***	-0.357***	0.005		0.070	0.017
		(0.015)	(0.025)	(0.024)		(0.074)	(0.027)
Ln(Precipitation)		0.150***	0.022**	0.028		0.260***	0.029
		(0.009)	(0.009)	(0.017)		(0.027)	(0.018)
Ln(Temperature)		-0.035**	-0.029	0.011		-0.044	0.032
		(0.014)	(0.021)	(0.063)		(0.028)	(0.068)
Ln(Wind speed)		-0.046***	-0.031***	-0.044***		0.032	-0.041***
		(0.011)	(0.007)	(0.009)		(0.025)	(0.009)
Ln(Gasoline tax)		-0.010	-0.078***			0.318***	
		(0.027)	(0.017)			(0.086)	
Ln(Diesel tax)		-0.101***	-0.002			-0.279***	
		(0.024)	(0.013)			(0.058)	
Ln(Gasoline price)		1.430***	0.742***				
		(0.188)	(0.106)				
Ln(Diesel price)		-1.347***	-0.537***				
		(0.160)	(0.091)				
Constant	9.057***	2.089***			4.673***	8.616***	
	(0.081)	(0.174)			(0.132)	(1.093)	

(B) First Stage

dependent variable: Ln(On-road daily VKT)

Interaction term between 1947 highways plan and fuel prices					0.002***	0.0003***	0.0001***
					(0.000)	(0.000)	(0.000)
City FE	No	No	Yes	Yes	No	No	Yes
Year and State FE	No	No	No	Yes	No	No	Yes
Observations	5,240	4,150	4,149	4,097	5,240	4,150	4,097
R-squared	0.089	0.878	0.172	0.021	-0.609	0.463	-0.348
Kleibergen-Paap rk Wald F-test					1,276	33.74	17.52

Notes. Panel (A) is the main result. The dependent variables is ln(aggregated $PM_{2.5}$ concentrations) in all columns. Panel (B) is the first stage result. The dependent variable is ln(On-road daily VKT) and the control variables are also included in the first stage regression in Column 6 and 7. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Panel (A) of column 5 and 6 are the main IV estimation result from estimating the second-stage. In addition, the specification of column 6 is conditional on a complete set of control variables. The elasticity of the aggregated $PM_{2.5}$ concentrations with respect to the on-road daily VKT is 63.4% and 68.5%, indicating that a 1% increase in on-road daily VKT would result in approximately 0.63% and 0.69% increase in the aggregate level of $PM_{2.5}$ concentrations for column 5 and 6, respectively. The elasticities are statistically significant at all conventional levels.

Lastly, consider column 7. This column is the preferred IV estimation resulting from estimating the second-stage, equation (5). The specification is conditional on a complete set of control variables, CBSA fixed effect, and the interaction term between time fixed effect and state fixed effect. Estimating the elasticity of aggregated $PM_{2.5}$ concentrations with respect to on-road daily VKT yields a coefficient smaller in magnitude relative to that in columns 5 and 6, from the elasticity of 63.4% and 68.5%, to 23.7%. However, the elasticity obtained from the preferred specification in column 7 is not statistically different from zero.

Overall, the results obtained from IV estimations suggest that one additional percent of on-road daily VKT would lead to an increase in the aggregated concentrations of $PM_{2.5}$ in the U.S. cities, ranging between 0.63% and 0.69%. When compare the IV estimation results with the OLS estimation results. These obtained elasticities from IV estimates are dramatically larger than the preferred OLS baseline estimation. This indicates that omitted variables correlated with on-road vehicle usage and concentrations of $PM_{2.5}$ cause economically important bias under the OLS estimates of the relationship between on-road transportation and $PM_{2.5}$ concentrations. However, if we restrict attention to the preferred specification, column 7, then on-road transportation does not significantly affect the aggregate concentrations of $PM_{2.5}$. Accordingly, the research hypothesis stating that "*On-road transportation is positively related to ambient $PM_{2.5}$ concentrations in urban areas"* is rejected.

5.3 Robustness checking

This study provides a series of additional estimates to verify the stability of the estimated relationship between on-road vehicle usage and $PM_{2.5}$ concentrations results presented in Table 5.1. Two additional estimates are (i) average traffic intensity and median $PM_{2.5}$ concentrations, and (ii) aggregated CO_2 emissions from on-road transportation sector and aggregated $PM_{2.5}$ concentrations.

5.3.1 Average traffic intensity and median $PM_{2.5}$ concentrations

In the first part of robustness checking, this study employs $PM_{2.5}$ concentrations calculated at the median value per CBSA as an alternative measure of ambient $PM_{2.5}$ levels apart from the aggregate value presented in the main estimates. In addition, the study also

employs an average traffic intensity per CBSA as an alternative measure of on-road vehicle use.

Data on the median $PM_{2.5}$ concentrations from 2001-2016 are also retrieved from the satellite average annual $PM_{2.5}$ concentrations GeoTIFF raster provided by NASA's Socioeconomic Data and Applications Center. The process in assigning the concentrations of satellite $PM_{2.5}$ data into the selected 381 CBSAs in the conterminous U.S., Alaska and Hawaii, has been performed in the similar manner as in section 3.1. However, by taking the Zonal Statistics tool, the $PM_{2.5}$ concentration value of each CBSA is calculated as median value of all satellite $PM_{2.5}$ grid cells that fall within each CBSA polygon. For an alternative measure of on-road vehicle use, average traffic intensity per CBSA is computed by dividing the aggregated on-road daily VKT by the size of CBSA. Overall, the mean value of the median $PM_{2.5}$ concentrations is 8.74 $\mu g/m^3$ per CBSA, while the mean value of the average traffic intensity is 12.78.

Throughout the first part of robustness checking, the dependent variable is the natural logarithm of median $PM_{2.5}$ concentrations in every column, while the measure of driving is the natural logarithm of average traffic intensity in all specifications. The unit of observation is the CBSA. Additionally, in each column of Table 5.2, this study estimates a specification similar to that of all columns as in Table 5.1, with CBSA fixed effect, the interaction term between time and state fixed effects, as well as a full set of control variables

Columns 1, 2, 3, and 4 of panel (A) in Table 5.2 report the results of OLS estimations of on-road transportation on $PM_{2.5}$ concentrations. Generally, OLS estimates of median $PM_{2.5}$ concentrations on average traffic intensity yield the elasticity consistent with the primary estimate in terms of magnitude and significance.

Consider results from the preferred instrumental variable estimations. Column 5, 6 and 7 of panel (B) reports that the three specifications satisfy the relevance condition as the Kleibergen-Paap rk Wald F-statistics tests on the interaction term between the 1947 interstate highways plan and fuel prices coefficient are larger than rule of thumb, 10. Focusing on the preferred specification (column 7), which includes a complete set of control variables, CBSA fixed effect, and the interaction term between time and state fixed effects. Main IV estimate result in panel (A) of column 7, reports an elasticity of 20%, which is slightly lower than the elasticity of 23.7% obtained from the primary estimate. Additionally, both elasticities are not significantly different from zero.

Generally, these results indicate that the findings appear to be robust to different on-road transportation measures. Measuring on-road transportation by average traffic intensity and measuring $PM_{2.5}$ concentrations at the median value provide consistent results that on-road transportation does not significantly affect the concentrations of $PM_{2.5}$ in urban areas.

Table 5.2

Average traffic intensity and median $PM_{2.5}$ concentrations

(A) Main result	(1) OLS	(2) OLS	(3) OLS, FE	(4) OLS, FE	(5) IV	(6) IV	(7) IV, FE
Ln(Average traffic intensity)	0.053***	-0.043***	-0.009	-0.005	-0.041***	0.248*	0.199
	(0.003)	(0.005)	(0.014)	(0.007)	(0.015)	(0.135)	(0.156)
Ln(Population density)		0.220***	0.171***	0.055		-0.200	-0.178
		(0.009)	(0.065)	(0.038)		(0.195)	(0.180)
Ln(Industrial activities)		0.146***	0.180***	-0.022**		0.187***	-0.030**
		(0.009)	(0.017)	(0.011)		(0.028)	(0.013)
Ln(Traffic congestion)		-0.018	0.045*	-0.002		-0.227**	-0.057
		(0.012)	(0.025)	(0.012)		(0.098)	(0.045)
Ln(GDP)		-0.193***	-0.361***	0.004		-0.160***	0.014
		(0.009)	(0.025)	(0.026)		(0.016)	(0.027)
Ln(Precipitation)		0.159***	0.024**	0.030*		0.199***	0.030*
		(0.006)	(0.010)	(0.018)		(0.023)	(0.018)
Ln(Temperature)		0.030***	-0.027	0.009		0.060***	0.027
		(0.010)	(0.021)	(0.063)		(0.016)	(0.066)
Ln(Wind speed)		-0.008	-0.032***	-0.044***		0.017	-0.041***
		(0.008)	(0.007)	(0.009)		(0.014)	(0.009)
Ln(Gasoline tax)		-0.037**	-0.078***			0.100	
		(0.017)	(0.017)			(0.067)	
Ln(Diesel tax)		-0.086***	-0.002			-0.167***	
		(0.015)	(0.013)			(0.042)	
Ln(Gasoline price)		0.935***	0.737***				
		(0.134)	(0.107)				
Ln(Diesel price)		-0.767***	-0.530***				
		(0.113)	(0.091)				
Constant	2.081***	2.261***			2.170***	4.697***	
	(0.005)	(0.118)			(0.015)	(1.128)	

(B) First Stage

dependent variable: Ln(Average traffic intensity)

Interaction term of 1947 Interstate highways plan and fuel price					0.001***	0.0001***	0.0001***
					(0.001)	(0.000)	(0.000)
City FE	No	No	Yes	Yes	No	No	Yes
Year and State FE	No	No	No	Yes	No	No	Yes
Observations	5,240	4,150	4,149	4,097	5,240	4,150	4,097
R-squared	0.082	0.427	0.170	0.021	-0.175	-0.231	-0.233
Kleibergen-Paap rk Wald F-test					270.23	7.11	17.52

Notes. Panel (A) is the main result. The dependent variables is ln(Median $PM_{2.5}$ concentrations) in all columns. Panel (B) is the first stage result. The dependent variable is ln(Average traffic intensity). Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

5.3.2 Aggregated CO_2 emissions from on-road transportation sector and aggregated $PM_{2.5}$ concentrations

In the second part of robustness checking, this study employs CO_2 emissions from on-road transportation sector as an alternative measure of driving to highlight the robustness of the estimated relationship between on-road vehicle usage and $PM_{2.5}$ concentrations results presented in Table 5.1.

The on-road CO_2 emissions have been used as an indicator of on-road vehicle usage by several empirical studies (e.g., Gately et al., 2015; Gurney et al., 2009; Li & Managi, 2021). Data on the average annual CO_2 emissions from on-road transportation sector are retrieved from the Database of Road Transportation Emission (DARTE) provided by the National Aeronautics and Space Administration. In the DARTE database, average annual on-road CO_2 emissions from motor gasoline and diesel fuel consumption are computed by combining the Federal Highway Administration's Highway Performance Monitoring System (HPMS) roadway-level vehicle miles traveled with state-specific emissions factors for multiple types of vehicles on six classes of urban and rural roads. This DARTE database, furthermore, provides insights into how urban areas contribute to climate change (see Gately et al., 2019). The average annual on-road CO_2 emissions are available at GeoTIFF raster file with 1-km spatial resolution over the conterminous U.S. This study repeats the same process as performed with the $PM_{2.5}$ concentrations data to assign the CO_2 emissions computed at the aggregate value to the selected 381 CBSAs. Overall, the mean value of on-road CO_2 emission is approximately 3,200 million metric tons per km^2.

Columns 1, 2, 3, and 4 of panel (A) in Table 5.3 report the results of OLS estimations of on-road transportation on $PM_{2.5}$ concentrations. The dependent variable is the natural logarithm of aggregated $PM_{2.5}$ concentrations in every column, while the measure of driving is replaced by the natural logarithm of aggregated on-road CO_2 emissions in all specifications. The unit of observation is the CBSA. Additionally, in each column of Table 5.3, this study estimates a specification similar to that of all columns as in Table 5.1 and 5.2, with CBSA fixed effect, interaction term between time and state fixed effects, as well as a complete set of control variables. Overall, the elasticity of OLS estimates of an alternative measure of driving on the aggregated $PM_{2.5}$ concentrations are more extensive than those in the primary estimate; however, all of the elasticities are positive. In column 1, this paper obtains an elasticity of 51.2% instead of 16.7%. Adding a full set of control variables in the specification in column 2 yields lower elasticity of 13.4%, statistically significant at the one percent level. In column 3, this study returns to the specification of column 1 but also includes CBSA fixed effect. Estimating the elasticity of $PM_{2.5}$ concentrations with respect to on-road CO_2 emissions gives a slightly larger elasticity of 14.2%. Lastly, adding control variables, CBSA fixed effects and interaction term between time and state fixed effects in the specification in column 4 yields a

dramatically lower elasticity of 2.3%. Based on these OLS estimates results, the effect of an alternative measure of on-road transportation—aggregated on-road CO_2 emissions—on aggregated $PM_{2.5}$ concentrations is minimal, consistent with the OLS estimates results using the on-road daily VKT as a primary measure of on-road transportation.

Next, considering results from the preferred method to investigate the relationship between on-road transportation and $PM_{2.5}$ concentrations, the instrumental variable estimations. Focusing on the preferred specification (column 7), which includes a complete set of control variables, CBSA fixed effect, and the interaction term between time and state fixed effects. The Kleibergen-Paap rk Wald F-statistics tests on the interaction term between the 1947 interstate highways plan and fuel prices coefficient, conditional on control variables, CBSA fixed effect, and the interaction term between time and state fixed effects, is 20.75, suggesting that interaction term between the 1947 interstate highways plan and fuel prices is a strong instrument in predicting CO_2 emissions from the on-road transportation sector, and the relevance condition is satisfied. In panel (A) of column 7, the elasticity from the 2SLS estimate is 47.4%, which is larger than the elasticity of 23.7% obtained from using on-road daily VKT as a primary measure of on-road transportation. Furthermore, both elasticities are not significantly different from zero.

Overall, these results suggest that the finding are robust to different on-road transportation measures. In the preferred IV estimations, both reports consistent results; on-road transportation does not significantly affect the concentrations of $PM_{2.5}$ in urban areas.

Table 5.3

Aggregated CO_2 emissions from on-road transportation sector and aggregated $PM_{2.5}$ concentrations

(A) Main result	(1) OLS	(2) OLS	(3) OLS, FE	(4) OLS, FE	(5) IV	(6) IV	(7) IV, FE
Ln(On-road CO_2 emissions)	0.512***	0.134***	0.142***	0.023	-0.017***	0.110***	0.474
	(0.007)	(0.013)	(0.032)	(0.018)	(0.005)	(0.036)	(0.378)
Ln(Population density)		0.169***	0.094	0.034		0.165***	-0.220
		(0.006)	(0.065)	(0.038)		(0.006)	(0.216)
Ln(Industrial activities)		0.127***	0.168***	-0.023**		0.116***	-0.032**
		(0.009)	(0.017)	(0.011)		(0.012)	(0.013)
Ln(Traffic congestion)		-0.063***	0.030	-0.004		-0.061***	-0.030
		(0.010)	(0.025)	(0.012)		(0.011)	(0.024)
Ln(GDP)		-0.281***	-0.378***	-0.002		-0.249***	-0.097
		(0.013)	(0.025)	(0.025)		(0.025)	(0.086)
Ln(Precipitation)		0.151***	0.026***	0.031*		0.149***	0.027
		(0.007)	(0.009)	(0.018)		(0.008)	(0.018)
Ln(Temperature)		0.020**	-0.026	0.008		0.036***	0.030
		(0.010)	(0.021)	(0.062)		(0.010)	(0.068)
Ln(Wind speed)		-0.004	-0.032***	-0.043***		0.003	-0.043***
		(0.008)	(0.007)	(0.009)		(0.008)	(0.009)
Ln(Gasoline tax)		0.003	-0.069***			0.007	
		(0.016)	(0.017)			(0.017)	
Ln(Diesel tax)		-0.093***	-0.003			-0.098***	
		(0.014)	(0.013)			(0.014)	
Ln(Gasoline price)		0.880***	0.697***				
		(0.135)	(0.108)				
Ln(Diesel price)		-0.705***	-0.495***				
		(0.115)	(0.092)				
Constant	-0.250*	1.703***			2.504***	1.876***	
	(0.144)	(0.136)			(0.099)	(0.262)	

(B) First Stage

dependent variable: Ln(On-road CO_2 emissions)

Interaction term of 1947 Interstate highways plan and fuel price					0.0021***	0.0003***	0.0000***
					(0.000)	(0.000)	(0.000)
City FE	No	No	Yes	Yes	No	No	Yes
Year and State FE	No	No	No	Yes	No	No	Yes
Observations	6,032	4,185	4,185	4,135	6,032	4,185	4,135
R-squared	0.451	0.427	0.173	0.022	-0.020	0.419	-0.162
Kleibergen-Paap rk Wald F-test					1,081	381.38	20.75

Notes. Panel (A) is the main result. The dependent variables is ln(Aggregated $PM_{2.5}$ concentrations) in all columns. Panel (B) is the first stage result. The dependent variable is Ln(On-road CO_2 emissions). Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

6. Discussion

This thesis aims to clarify whether on-road transportation is a significant source contributing to ambient $PM_{2.5}$ concentrations in urban areas and to understand the potential to reduce on-road traffic emissions further to improve air quality. To achieve that, investigation on the causal relationship between on-road transportation and $PM_{2.5}$ concentrations across metropolitan areas in the U.S. is performed by testing the proposed hypothesis of whether on-road transportation is positively related to the $PM_{2.5}$ concentrations in urban areas. Ultimately, this thesis seeks to answer the research question that *"Based on the most recent dataset, is emissions from on-road transportation a pollution source that significantly contributes to fine particulate matter ($PM_{2.5}$) concentrations in urban areas?"*.

6.1 Discussion of results

Based on the empirical evidence, this thesis does not find support for the proposed research hypothesis stating that *"On-road transportation is positively related to ambient $PM_{2.5}$ concentrations in urban areas"*. While according to the atmospheric science studies, a large number of existing literature (e.g., Amato et al., 2014; Davidson et al., 2005; Hodan & Barnard, 2004; Karagulian et al., 2015; Pant & Harrison, 2013) suggests that vehicle transportation on the roadway is positively related to the ambient concentrations of $PM_{2.5}$ in urban areas, evidence from the 381 metropolitan areas in the U.S. over the past sixteen years conversely shows the insignificant results. Based on the preferred instrumental variable estimations, the statistical results indicate that an additional kilometer of on-road vehicle traveled does not lead to a significant increase in the overall concentrations of $PM_{2.5}$ in U.S. cities. This, in other words, would suggest that on-road transportation is not a significant pollution source contributing to ambient $PM_{2.5}$ concentrations in urban areas at present.

Although, the empirical result of this thesis implies, contradictory to majority of the existing literature, that there is no significant increase in the overall $PM_{2.5}$ concentrations in urban areas when additional kilometers of vehicle driven on the roadway. This obtained result is somewhat unsurprising as it is noticeable from a real-world declining trend of $PM_{2.5}$ concentrations whereas an increasing trend of vehicle mileage over the past two decades (Figure 1.1). In addition, it is also observable from a growing trend of recent studies that there is a significant reduction in the contribution of on-road transportation to overall $PM_{2.5}$ concentrations in urban environments (Harrison et al., 2021; Li & Managi, 2021). This circumstance can potentially be explained by two main factors.

Firstly, the several successive decades of cleaner automotive technology improvement, clean air action, and stringent regulations have resulted in a significant reduction in emissions of $PM_{2.5}$, $PM_{2.5}$ precursors (i.e., VOCs, nitrogen oxides, sulfur oxides, and ammonia) and other

pollutants from transportation sectors (Mathissen et al., 2011; Thorpe & Harrison, 2008; Winkler et al., 2018). This is especially true of a direct emission from the vehicle tailpipes (exhaust emissions). In the U.S. in particular, the successive introduction of the federal Tier 2 motor vehicle emission standards and the California LEV II regulations were phase-in 2001-2009, brought new requirements for fuel quality such as advanced emission after-treatment devices (e.g., catalytic converters and particulate filters), while the ongoing federal Tier 3 motor vehicle emission standards and the California LEV III regulations that tighten nitrogen oxides, sulfur oxides, and VOCs limits for vehicle engines (Winkler et al., 2018; EPA, n.d.). As a result of motor vehicle emission and fuel standards and together with the Clean Air Act, tailpipe emission per vehicle fleet has decreased substantially, resulting in the significant decline in VOCs, nitrogen oxides, and sulfur oxides of about 60-80 percent since 1990, reduction in overall $PM_{2.5}$ concentrations roughly up to 41 percent since 2000, and a steady air quality improvement in most cities in the U.S. (EPA, n.d.; Mathissen et al., 2011; Thorpe & Harrison, 2008; Winkler et al., 2018). It is noted that as vehicle exhaust emissions have decreased, non-exhaust emissions (e.g., abrasion of tire wear, brake wear and road surface, the corrosion of other vehicle components) have become a relatively more important source of air pollution attributable to on-road transportation (Amato et al., 2014). However, non-exhaust emissions only contribute a much smaller share of the total $PM_{2.5}$ relatively to the exhaust emissions. This would potentially be another factor causing the insignificant effect of on-road transportation on $PM_{2.5}$ concentrations in the cities.

Secondly, the life cycle, physical and chemical properties, and the formation process of atmospheric particulate matter play a vital role in the variation of $PM_{2.5}$ concentrations in urban areas. As described in detail in the theoretical framework chapter, $PM_{2.5}$ is a highly variable and complex mixture of aerosol particles and chemical species. Its concentration levels heavily depend on a complex interplay between various factors, including altitude, the number of anthropogenic activities, geographic attributes, meteorological conditions, and atmospheric conditions present in a particular place (Davidson et al., 2005; Seinfeld & Pandis, 2016). While intuitively, an area with more increased vehicle tailpipe emissions would depict a higher $PM_{2.5}$ concentrations level than those with lower vehicle tailpipe emissions, this intuition, however, is not always correct. This is especially true of the secondary $PM_{2.5}$, where atmospheric chemistry and the chemical reaction between precursor pollutants are significantly influenced by surrounding environmental conditions (e.g., the intensity of solar radiation, temperature, humidity, and other chemical compounds present in the atmosphere). In addition, the interactions between the gases can be nonlinear, meaning that not all $PM_{2.5}$ precursors will always transform into fine particles; only those precursors with the optimal environmental conditions will become a $PM_{2.5}$ (Kelly & Fussell, 2012). Consequently, these

life cycles and the chemical formation process of $PM_{2.5}$ would potentially explain the insignificant effect of on-road transportation on $PM_{2.5}$ concentrations in urban areas.

6.2 Policy implications

This thesis has provided empirical evidence that on-road transportation does not lead to a significant increase in the overall concentrations of $PM_{2.5}$ in U.S. cities. This empirical evidence has several practical implications for policy-making, especially air quality management, and what could be expected from further reduction of on-road transportation emissions to improve urban's air quality in the future.

According to data and statistical scrutiny, the insignificant effect of on-road transportation on $PM_{2.5}$ concentrations in urban areas implies that the gains from any policy aimed at reducing on-road traffic emissions further to lower $PM_{2.5}$ concentrations in urban areas would be marginal to insignificant; this is especially the case in the U.S. and other developed worlds where there have been progressive advanced automotive technology improvements and stringent vehicle emission regulations (Harrison et al., 2021). Consequently, as the on-road transportation sector emits a much smaller to insignificant share of the total $PM_{2.5}$ emissions, other emission-reduction strategies can be a more cost-effective and practical policy in improving air quality in urban areas. For example, lowering $PM_{2.5}$ emissions from non-on-road transportation sources (e.g., domestic fuel burning and industries) and building unfavorable conditions for the formation of $PM_{2.5}$ precursor pollutants (e.g., lowering ammonia emissions and oxidizing agents like ozone and hydroxyl radical) would result in a more significant impact on air quality improvement. For future on-road transportation emission reduction, it might be more profitable to target reducing non-exhaust emissions (e.g., road dust suspension), which represent a small share of 20-25 percent in total (Mancilla & Mendoza, 2012) but have become a relatively more important source of air pollution attributable to on-road transportation (Amato et al., 2014). Additionally, it is interesting to note that shifting to zero-emission vehicles such as battery electric vehicles will yield only minor benefits for $PM_{2.5}$ reduction emitted from non-exhaust sources relative to modern internal combustion engine vehicles (Beddows & Harrison, 2021). This is due to an advanced improvement of modern internal combustion engines, and the generation of electricity or hydrogen for zero-emission vehicles can produce upstream emissions (Harrison et al., 2021).

6.3 Limitation and recommendation for future research

As in every research, the empirical analysis of this thesis is considered in light of its limitations. Firstly, since this thesis intentionally constructs the dataset at the CBSA level instead of at a finer scale, the analysis does not consider how different $PM_{2.5}$ concentrations are spatially distributed within a CBSA. Furthermore, the $PM_{2.5}$ concentration value is

computed at the aggregate value, and therefore is assumed to be homogeneous across a certain CBSA. Such might cause ecological inference fallacy, especially when attempting to mitigate air pollution for a specific district in a large metropolitan where there is a significant difference in $PM_{2.5}$ concentrations between each district. Secondly, since this thesis employed $PM_{2.5}$ concentrations at an average annual level, this restricts this study from providing exciting insights regarding temporal and seasonal variations (e.g., the contribution of on-road transportation on $PM_{2.5}$ concentrations in wintertime, summertime, burning season, or even during rush-hour and off-peak hours). Finally, the chemical characteristic, precursors' formation, and the reaction of the fine particles were not considered in the statistical investigation of the effect on on-road transportation on $PM_{2.5}$ concentrations. Therefore, the results cannot provide insights on the aspect of the chemical mechanisms, which have an influential impact on the level of $PM_{2.5}$ concentrations in urban areas.

In future studies, more detailed remote sensing $PM_{2.5}$ concentrations and $PM_{2.5}$ precursor pollutants data with temporal and seasonal variations at a finer scale should be applied to the analyses. Furthermore, as mentioned in the theoretical framework chapter, on-road transportation contributes to ambient $PM_{2.5}$ concentration levels through three general processes: a direct emission from the vehicle tailpipes, emissions due to wear and tear of vehicle parts and re-suspension of dust, and a formation of traffic-emitted gaseous precursor emissions in the atmosphere through the chemical gas-to-particle conversion process. Therefore, investigating the causal relationship of each contribution process on $PM_{2.5}$ concentrations would quantify the effect of on-road transportation on air pollution more precisely. In addition, more information about vehicles, such as vehicle type, fuel types, quantity, the technology of engines, among others, are encouraged to be included in the investigation of the causal effect of on-road transportation in $PM_{2.5}$ concentration in the future. Lastly, since vehicle emission standards and regulations are one of the main factors in explaining the insignificant effect of on-road transportation on $PM_{2.5}$ concentrations in U.S. cities. However, the vehicle emission standards and regulations are also different worldwide. Therefore, employing sample data from less developed world cities with strong controls on traffic emissions (e.g., China and Turkey) and less developed world cities with poor controls on traffic emissions (e.g., India) might yield different results that lead to a different approach to air pollution improvement.

7. Conclusion

Adverse health implications attributable to the ambient air pollution exposure, especially the fine particulate matter ($PM_{2.5}$), are particularly critical for those living in urban areas. While extensive scientific studies conducted in the last three decades reveal that on-road transportation is one of the significant contributors of $PM_{2.5}$ concentrations in urban areas, more recent studies conversely find that vehicle transportation on the roadways merely represents a relatively small contribution of total $PM_{2.5}$ in the cities due to the continual automotive technology improvement and stringent emission regulations. Such contradiction raises arguments about whether on-road transportation a major source of ambient $PM_{2.5}$ in urban areas at present and what could be expected from further reduction of on-road transportation emissions to improve urban's air quality in the future. Accordingly, this thesis has scrutinized the relationship between on-road transportation and concentrations of $PM_{2.5}$, with an attempt to answer the following research question: *"Based on the most recent dataset, is emissions from on-road transportation a pollution source that significantly contributes to fine particulate matter ($PM_{2.5}$) concentrations in urban areas?"*.

By executing instrumental variable estimations, data on 381 CBSAs from 2001-2016 and statistical results suggest that an additional kilometer of on-road vehicle traveled does not lead to a significant increase in the overall concentrations of $PM_{2.5}$ in U.S. cities. This, in other words, would suggest that on-road transportation is at present not a significant pollution source contributing to ambient $PM_{2.5}$ concentrations in urban areas. This empirical evidence implies that the gains from any policy aimed at reducing on-road traffic emissions further to lower $PM_{2.5}$ concentrations in urban areas would be marginal to insignificant. Consequently, as the on-road transportation sector emits a smaller to insignificant share of the total $PM_{2.5}$ emissions, other emission-reduction strategies can be a more cost-effective and practical policy in improving air quality in urban areas.

Nevertheless, this thesis is not without limitations. Further research on on-road transportation and $PM_{2.5}$ concentrations is advised to consider more detailed remote sensing air pollution data with temporal and seasonal variations, and more information about vehicles, such as vehicle type and fuel types. Additionally, the chemical mechanisms of atmospheric particulate matter are suggested to be included in the scrutiny. Going forward, it will be essential to have a more holistic view of all the three processes on-road transportation contributes to ambient $PM_{2.5}$ concentration levels and assess the most cost-effective approaches to achieve the desired air pollution improvements in urban areas.

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Appendices

Appendix A

Summary of variables and data sources

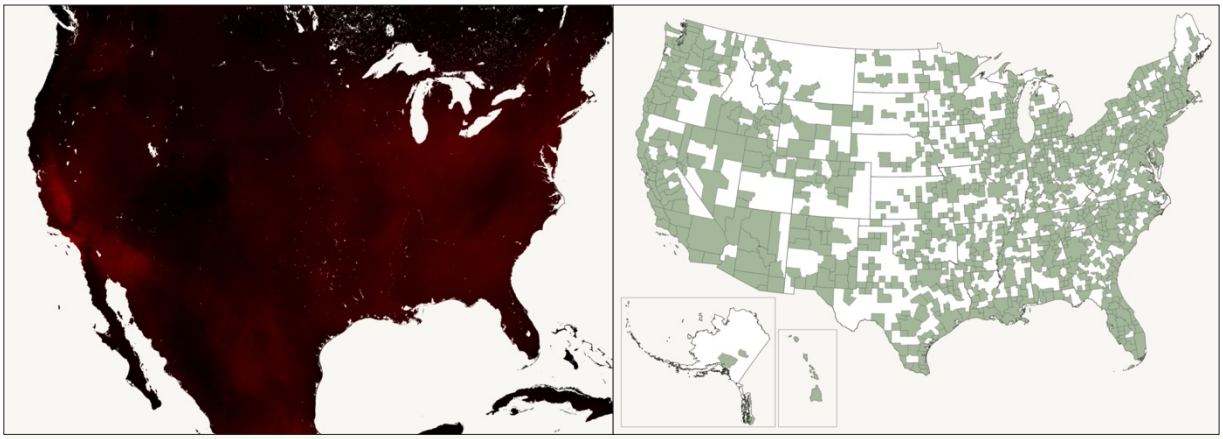
Table A1

Summary of variables and data sources

Variables	Sources	
	Name of Organization	URL
Dependent variable		
(1) Average annual $PM_{2.5}$ concentrations	NASA's Socioeconomic Data and Applications Center (SEDAC)	https://sedac.ciesin.columbia.edu/data/set/sdei-global-annual-gwr-pm2-5-modis-misr-seawifs-aod-v4-gl-03/data-download
Independent variable		
(2) On-road daily VKT	The U.S. Department of Transportation - Federal Highway Administration (FHWA)	https://www.fhwa.dot.gov/policyinformation/quickfinddata/qfroad.cfm
Control variables		
(3) Annual Average Daily Traffic (AADT)	The U.S. Department of Transportation - Federal Highway Administration (FHWA)	https://www.fhwa.dot.gov/policyinformation/quickfinddata/qfroad.cfm
(4) Population density	WorldPop	https://www.worldpop.org/geodata/summary?id=44766
(5) Industrial employment	The U.S. Census Bureau's Longitudinal Employer-Household Dynamics (LEHD)	https://j2explorer.ces.census.gov/explore.html#1343062
(6) Temperature (7) Precipitation (8) Wind speed	WorldClim global climate and weather data	https://worldclim.org/data/monthlywth.html
(9) Gasoline and Diesel Prices	The U.S. Energy Information Administration (EIA)	https://www.eia.gov/dnav/pet/pet_pri_gnd_dcus_nus_a.htm
(10) Gasoline and Diesel Taxes	The U.S. Department of Transportation - Federal Highway Administration (FHWA)	https://www.fhwa.dot.gov/policyinformation/statistics/2018/MF205.cfm
(11) Annual GDP	The U.S. Bureau of Economic Analysis (BEA).	https://www.bea.gov/
Robustness checking		
(12) On-road CO_2 emissions	National Aeronautics and Space Administration	https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1735

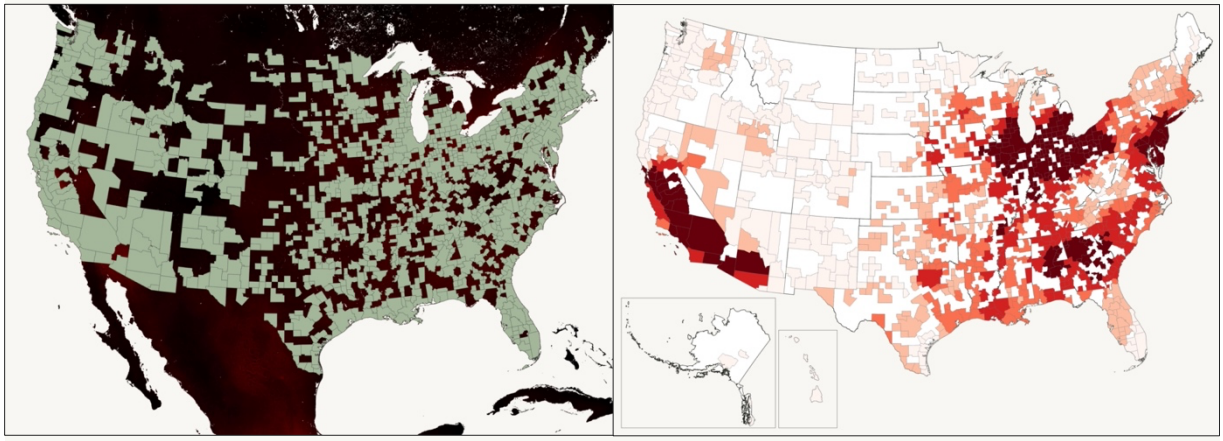
Appendix B

Process in assigning the satellite $PM_{2.5}$ concentrations GeoTIFF raster into the selected CBSAs in the United States boundary shapefile



(A) Satellite $PM_{2.5}$ concentrations GeoTIFF raster

(B) Core Based Statistical Areas (CBSAs) polygons shapefile



(C) Overlaying CBSAs polygons shapefile on satellite $PM_{2.5}$ concentrations GeoTIFF raster

(D) Output shapefile

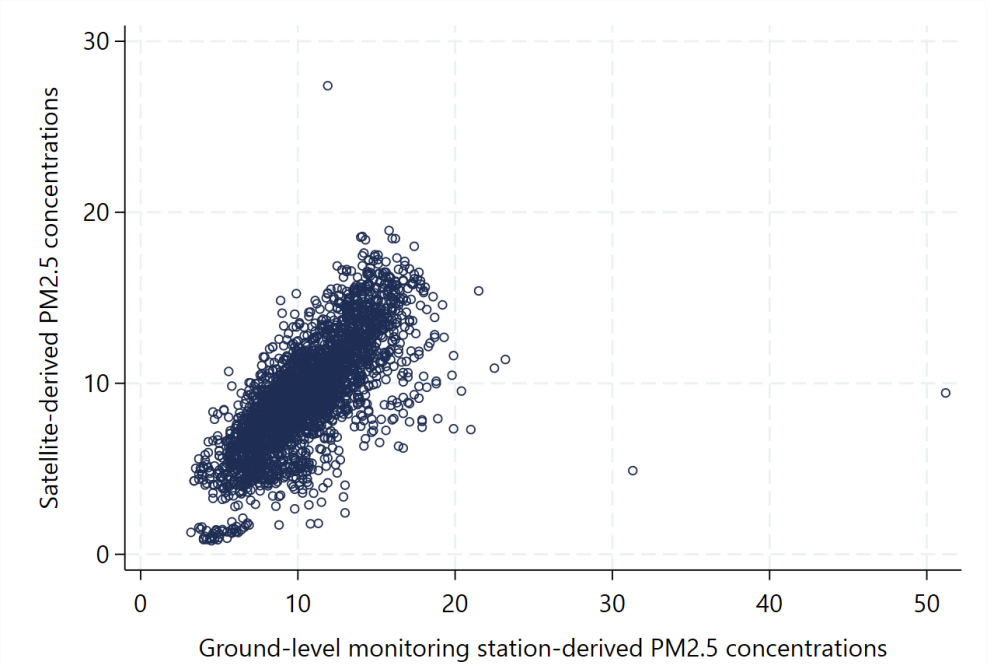
Note. **Panel A** exhibits a GeoTIFF raster of satellite $PM_{2.5}$ concentrations. The raster contains a grid cell resolution of 0.01x0.01-degree, covering the global land surface from 70 degrees north to 55 degrees south. The brighter red area represents a higher level of $PM_{2.5}$ concentrations. **Panel B** presents all Core Based Statistical Areas (CBSAs) polygon shapefile over the contiguous United States, Alaska and Hawaii. The green areas are the CBSAS, while the white areas are non CBSAs. In **Panel C**, the CBSAs polygons are overlaid on the satellite $PM_{2.5}$ concentrations GeoTIFF raster. By doing so, we determine which satellite $PM_{2.5}$ grid cells overlay consolidated the CBSAs by using the Zonal Statistics tool in the GIS software. Lastly, **Panel D** is the output shapefile after assigning the satellite $PM_{2.5}$ concentrations GeoTIFF raster into CBSAs. The red area represents high level of $PM_{2.5}$ concentrations, whereas orange to light pink areas show lower concentrations, respectively.

Appendix C

Scatter plot demonstrating the correlation between $PM_{2.5}$ concentrations derived from ground-level monitoring stations and satellite

Figure C1

Scatter plot of the correlation between $PM_{2.5}$ concentrations derived from ground-level monitoring stations and satellite

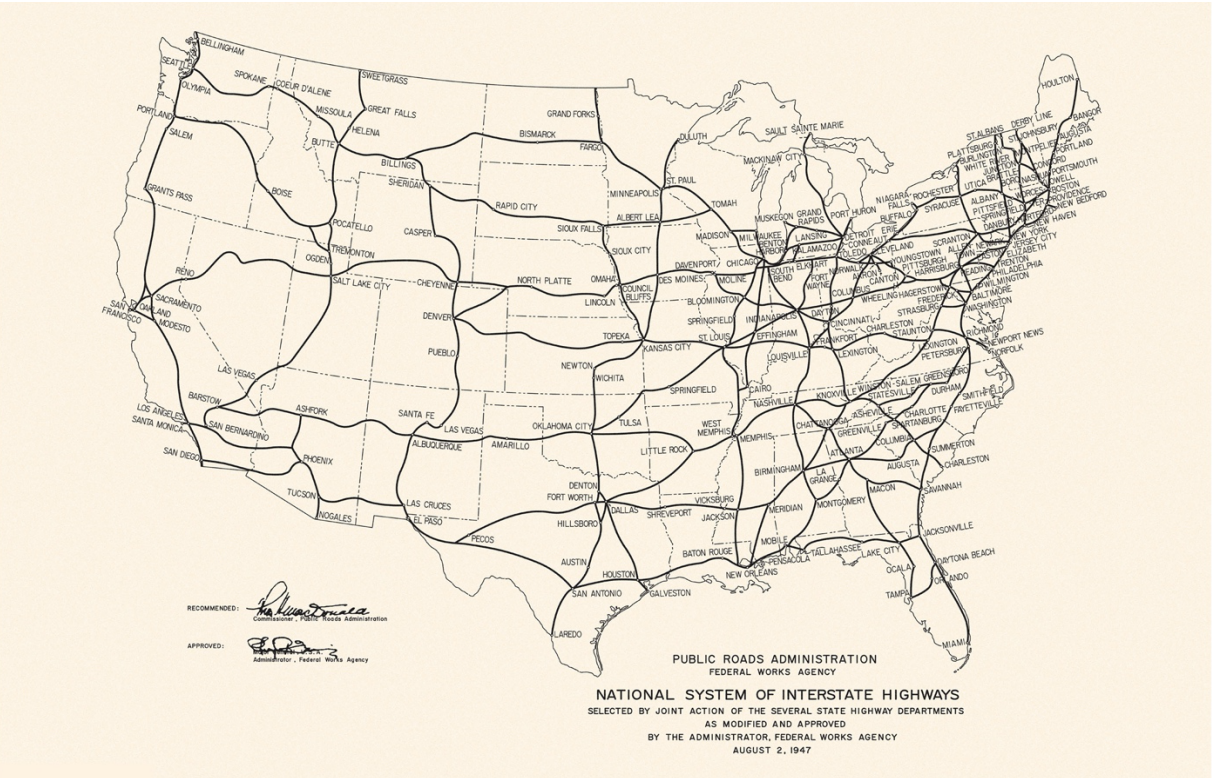


Note. Vertical axis represents an average annual $PM_{2.5}$ concentrations, as obtained from the satellite-derived measures. Horizontal axis represents average annual $PM_{2.5}$ concentrations obtained from ground-level monitoring station.

Appendix D
1947 plan of the interstate highway system

Figure D1

The 1947 plan of the interstate highway system



Note. Retrieved from Duranton and Turner (2011).

Appendix E

Pairwise correlation coefficient

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
(1) Aggregate $PM_{2.5}$	1.000												
(2) On-road daily VKT	0.060	1.000											
(3) Population density	0.153	0.702	1.000										
(4) Industrial activities	0.065	0.585	0.670	1.000									
(5) Traffic congestion	0.029	0.453	0.448	0.415	1.000								
(6) GDP	0.036	0.632	0.741	0.882	0.341	1.000							
(7) Precipitation	0.322	0.015	0.114	-0.032	0.049	-0.004	1.000						
(8) Temperature	-0.068	0.012	0.004	0.087	0.221	0.023	0.192	1.000					
(9) Wind speed	0.010	-0.020	0.072	-0.029	-0.080	0.007	0.123	-0.211	1.000				
(10) Gasoline price	-0.348	0.002	0.022	-0.037	-0.036	0.041	0.001	0.023	0.134	1.000			
(11) Diesel price	-0.349	0.002	0.022	-0.036	-0.038	0.041	0.004	0.015	0.132	0.996	1.000		
(12) Gasoline tax	-0.185	-0.065	-0.004	-0.052	-0.011	-0.026	-0.152	-0.282	0.019	0.163	0.163	1.000	
(13) Diesel tax	-0.153	-0.067	-0.002	-0.068	-0.049	-0.061	-0.018	-0.225	0.068	0.073	0.074	0.756	1.000