

TRANSPORTATION AND WATER QUALITY IN THE U.S.

A Thesis

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by

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ABSTRACT

The relationship between transportation and air quality has been widely studied while little did we know about transportation and water quality in economic papers, despite its importance emphasized by the Clean Water Act. This study estimates the effect of annual average daily traffic (AADT) on lead pollution in surface water across the United States. The results show that one million more vehicles within 2 miles of the water will lead to 1.95 ug/L increase in lead concentration and the effect is mainly localized. The total estimated increase in lead in water due to heavier traffic amounts to 1.33 ug/L from 2011-2017, accounting for about 45% of the sample mean lead concentration. This paper then confirms that the mobilizing effect dominates the diluting effect, meaning the heavy storm events will result in worsening highway runoff quality for lead. This study also indicates that the effect is larger in rural areas than urban areas. Finally, policy implications are discussed to deal with the negative externalities brought by the transportation sector.

BIOGRAPHICAL SKETCH

Yongfan Zhao was born in Chengdu, Sichuan Province in southwestern China. Sichuan is endowed with many beautiful mountains, rivers, and lakes. The abundant water resources also benefit Sichuan in developing hydroelectricity, tourism, etc. Yongfan left her hometown and went to Nankai University in Tianjin for her undergraduate study in economics. During the four years, Yongfan worked in an international NGO and conducted projects related to climate change, water stress, and water quality. Yongfan also completed her undergraduate thesis related to firms' environmental performance. With her strong interest in environmental economics, Yongfan came to the US to pursue her master study in applied economics and management at Cornell University. She is currently involved in projects related to water resources, global climate change, water quality, and transportation. She has also interned in an international organization to help tackle real-world environmental issues. Cherishing the idea of building a sustainable planet, Yongfan will continue her study at Cornell Dyson as a PhD student this coming fall.

This document is dedicated to my parents and grandparents.

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CHAPTER 1

INTRODUCTION

A lot of economic papers have studied the impact of transportation on air quality. For example, Gendron-carrier et al. (2022) [1] studied the effect of subway openings on urban air pollution worldwide. Li et al. (2019) [2] looked at the subway expansion and air quality in Beijing. Chen and Whalley (2012) [3] investigated the effect of urban rail transit on air quality in Taipei. However, there is no economic literature related to transportation and water quality despite its importance emphasized by the US EPA's National Pollutant Discharge Elimination System (NPDES) program under the Clean Water Act (CWA). The transportation sector is mainly considered as a nonpoint source of water pollution since the pollutants are from the exhaust gas, paints, wheel weights, and brake wear of the vehicles passing by. During heavy storm events, the rains or snows wash the pollutants on the roads into nearby water bodies (i.e., highway runoff), resulting in worsening water quality. Existing water quality studies in economics primarily focus on point source pollution from industrial activities (Keiser and Shapiro, 2019) [4] or nonpoint source pollution from agricultural sectors (Elbakidze et al., 2022 [5]; Taylor and Heal, 2021 [6]), neglecting the transportation sector.

There is environmental engineering literature that looks into the highway runoff characteristics in the US. Table 1.1 summarizes the related engineering literature on highway runoff. The earliest paper dates back to late 1970s (Bourcier and Hindin, 1979) [7]. The first nationwide study to report lead concentration in highway runoff is the US EPA study under the Nation Urban Runoff Program (USEPA, 1983) [8]. Several years later, the Federal Highway Administration

(FHWA) conducted a highway runoff characterization study throughout the US (Driscoll et al., 1990) [9]. More state-level studies were performed to analyze the pollutants concentration in highway runoff during the 1990s and 2000s, respectively. These engineering studies, however, are mostly limited to one specific region/state and involve few monitoring sites whose data are only collected in a single wet season. Moreover, previous engineering research mainly focuses on the measurement of different water quality indicators and related descriptive analysis. There is one paper that finds significant relationships between annual average daily traffic (AADT) and various water pollutants in California using multiple linear regressions (Kayhanian et al., 2003) [10]. Still, a more comprehensive study is needed to understand the relationship between transportation and water pollution for the whole US.

Table 1.1: Highway Runoff Studies and Lead Concentration in the US

Location	Year	Reference	Lead Concentration (ug/L)
Washington	1979	Bourcier and Hindin [7]	1860
Nationwide, USA	1983	US EPA 1983 [8]	182
Nationwide, USA	1990	Driscoll et al. [9]	400
Cincinnati	1997	Sansalone and Buchberger [11]	64
Texas	1998	Barrett et al. [12]	53
California	2000	Kayhanian and Borroum [13]	89
California	2003	Kayhanian et al. [10]	93
Texas	2006	Barrett et al. [14]	13
California	2006	Han et al. [15]	26
California	2007	Kayhanian et al. [16]	48
Texas	2008	Li and Barrett [17]	10
California	2009	Lau et al. [18]	33

Note: This table is adapted from Kayhanian (2012). [19]

This paper looks at the effect of nearby highway traffic on lead pollution in water in the US using segment-level annual average daily traffic (AADT) data and granular monitor-level lead concentration data. The reason why lead is analyzed in this paper is that lead pollution is closely related to transportation and

even a tiny amount of lead could cause great damage to our health as well as local ecosystems. For lead and transportation, Table 1.1 summarizes lead concentration documented in relevant highway runoff studies. From the 1970s to the 2000s, the lead concentration in the water of the US falls significantly, which is mainly due to the phase-out of leaded gasoline starting in 1973 (Kayhanian, 2012) [19]. The sample mean of lead concentration in this paper is 2.97 ug/L, which is much lower than earlier studies. However, we still cannot neglect the lead pollutants brought by the transportation sector since lead can be a huge threat to our health. Specifically, when people breathe in dust containing lead or ingest food or liquids containing lead, the lead first reaches the lung or stomach and then enters the bloodstream. Once in the blood, lead travels to the “soft tissues” and organs such as the liver, kidneys, brain, muscles, and heart. After several weeks, most of the lead moves into the bones and teeth (Clay et al., 2021) [20]. A lot of economic papers have pointed out that lead has adverse effects on neurological development (e.g., IQ, educational outcomes, and behavioral outcomes) of young children (Reyes 2015 [21]; Aizer et al., 2018 [22]; Hollingsworth et al., 2022 [23]; Gazze et al., 2022 [24]). Also, the decrease in lead exposure has a positive effect on fertility and results in a decrease in elderly mortality (Hollingsworth and Rudik, 2021 [25]; Clay et al., 2021).

To my knowledge, this paper is the first empirical study to provide a direct link of road traffic and lead pollution in the water of the whole United States, which is a big step forward compared to previous engineering literature. My estimation shows that, on average, one million more cars within 2 miles are associated with 1.95 ug/L increase in lead concentration in adjacent surface water, holding all else equal. The effect gets smaller as the buffer zone enlarges. The magnitude of the effect is relatively large in that the total increase in lead in re-

ceiving water due to the increase in AADT during 2011-2017 equals 1.33 ug/L, which is about 45% of my sample mean lead concentration. Rainfall intensity can also affect the concentration of highway runoff. The monthly regression shows that the effect of AADT on lead in water becomes stronger when there is more precipitation, confirming the mobilizing effects mentioned in previous engineering literature. Furthermore, the mobilizing effect becomes the strongest when the monthly total precipitation exceeds 450 mm. The extension part indicates that cars driving 10-15 miles away from the water produce the largest negative effect on lead contamination in water. Lastly, I find that the above effects are larger in rural areas than urban areas, partly because the portion of heavy duty trucks driving on the rural highways is larger than urban roads.

My results have several policy implications. First, to alleviate the negative effect on water quality brought by highway traffic, source controls could be adopted. For example, enforcing EPA's two initiatives- National Lead Free Wheel Weight Initiative & Copper-Free Brake Initiative to become laws could benefit the contaminated water in the US. Second, establishing a nationwide specialized monitoring system for highway runoff could contribute to better performance of best management practices (BMPs). Third, state-level mitigating measures like designing vegetated filter strips along highways, creating detention and retention ponds, street sweeping, and preservation of natural vegetation could be used more often.

The remainder of the paper is organized as follows: Chapter 2 provides background information about the NPDES program and the relationship between transportation and lead contamination in the US. Chapter 3 and Chapter 4 introduce the data and empirical strategies. Chapter 5 presents the estimation

results of the effect of AADT on lead pollution in water, along with robustness checks, extension analysis, and heterogeneity analysis. Chapter 6 concludes and discusses the implications of the findings.

CHAPTER 2 BACKGROUND

2.1 The NPDES Permit Program

The National Pollutant Discharge Elimination System (NPDES) permit program, created in 1972 by the Clean Water Act (CWA), helps address water pollution by regulating point sources that discharge pollutants to the waters of the United States.¹ Apart from EPA, many states are also assigned as permitting authorities to implement the program.

One big part of NPDES is its stormwater program, which is designed to prevent stormwater runoff from washing harmful pollutants into local surface waters. It regulates discharges from three potential sources: municipal separate storm sewer systems (MS4s), construction activities, and industrial activities. Starting from 1990, the Phase I stormwater regulation requires medium and large cities or certain counties with populations of 100,000 or more to obtain MS4s NPDES permit. The Phase II period from 1999 includes small MS4s like Census-defined urbanized areas and non-traditional MS4s such as Departments of Transportation (DOTs). The permits require regulated MS4s to develop, implement, and enforce a stormwater management program (SWMP) and typically include requirements related to: construction, illicit discharge detection and elimination, pollution prevention/good housekeeping, post-construction, public education and outreach, public involvement/participation, program effectiveness, and total maximum daily loads.

¹EPA's website about NPDES: <https://www.epa.gov/npdes/about-mpdes>

2.2 Transportation and Lead

The major sources of lead on the highways are fuel and motor oil combustion, paints, wheel weights, brake wear, and resuspension of enriched road dust (Lough et al., 2005 [26]; Murakami et al., 2007 [27])². Since EPA has phased out leaded gasoline from 1973, the tailpipe emission of lead is no longer a big concern in our context. Another regulation was adopted by EPA in 1977 to ban the inclusion of lead in paint products. So, the lead legacy from paints in old cars is also not considered a big issue in this paper. However, a more likely source of the persistent lead enrichment on the highway is lead wheel weights which are dropped from vehicle wheels and pulverized by traffic (Root, 2000) [28]. An average of 4.5 ounces of lead is clipped to the wheel rims of every automobile in the United States. According to a 2003 United States Geological Survey (USGS) national study, approximately 2,000 tons of lead wheel weights were lost from vehicles into the environment each year. In 2009, EPA established a National Lead Free Wheel Weight Initiative³ as a volunteer program to encourage the use of lead-free alternatives. Following this, 8 states⁴ have chosen to enact laws prohibiting lead wheel weights. Yet in 2017, lead wheel weights remain legal in 42 states.

Another possible source of lead on the road is the brake pad. Each time the semi-metallic brake pads squeeze against the wheels' rotors, tiny amounts of metal dust containing lead are deposited along the roadway and washed into water bodies by rain or snow (Nixon & Saphores, 2007) [29]. EPA's Copper-Free

²For pictures of wheel weights and brake pads, please see the appendix.

³EPA's website: <https://archive.epa.gov/epawaste/hazard/wastemin/web/html/nlffwi.html>

⁴These states are Washington, California, Illinois, Maine, Vermont, Minnesota, New York, and Maryland.

Brake Initiative in 2015⁵ has called for reducing copper, lead, and other metals in brake pads. At the state level, California and Washington adopted relevant laws in 2010 and 2015 to restrict/ban lead in brake pads. Still, leaded brake pads are widely used in vehicles in the US.

It is well documented that lead causes great harm to people's health and there is no safe level of lead. Hence, it is important to quantify the effect of highway traffic on lead concentration in water.

⁵EPA's website: <https://www.epa.gov/npdes/copper-free-brake-initiative>

CHAPTER 3

DATA

3.1 EPA's Water Quality Portal

The lead concentration data (unit: $\mu\text{g}/\text{L}$) are obtained from EPA's Water Quality Portal's¹ Storet repositories. I follow the methods described in Keiser & Shapiro (2019), including limiting to rivers, streams, lakes, reservoirs, or impoundments; converting measurements to the same unit; winsorizing at the 99th percentile. I then calculate the yearly and monthly average lead concentration for each monitoring station between 2011-2017. The figure below shows the distribution of 14,791 lead monitoring stations. The darker color represents heavier mean lead pollution in water during the seven years.

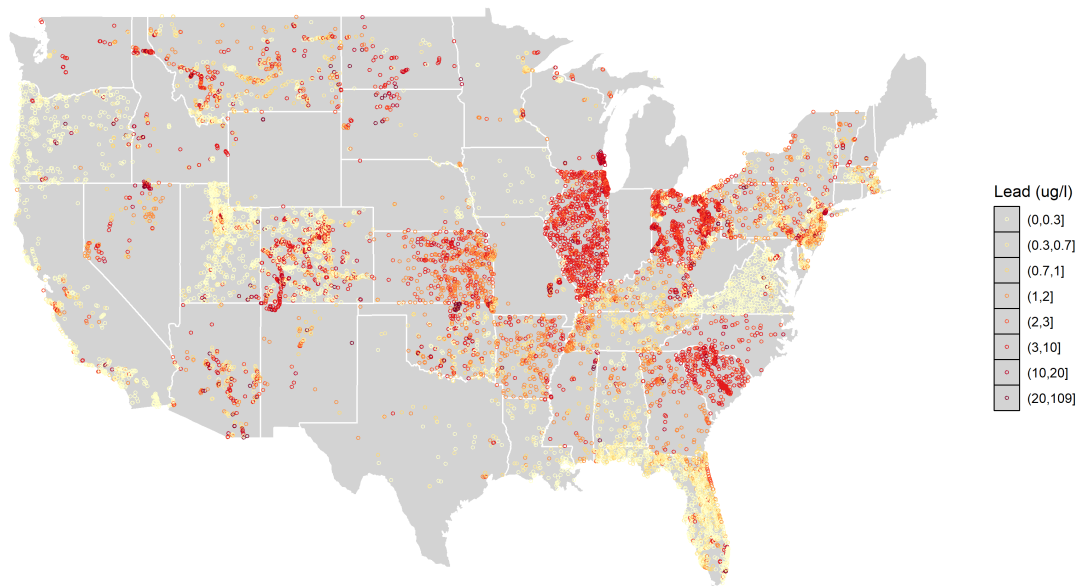


Figure 3.1: Lead Monitoring Stations in the US (2011-2017)

¹EPA's Water Quality Portal: <https://www.waterqualitydata.us/>. The portal provides over 10,000 types of daily monitor-level water quality indicators for the whole US.

3.2 HPMS

The Highway Performance Monitoring System (HPMS) is a national level highway information system that includes detailed segment-level data on the extent, condition, performance, use, and operating characteristics of the nation's highways². The variable of interest is Annual Average Daily Traffic (AADT), which is the total volume of vehicle traffic of a highway for a year divided by 365 days.

To calculate the nearby traffic volume for each monitor, I first merge the original state-level highway line features into one national shapefile in ArcGIS Pro. To avoid double counting of AADT, I dissolved the segments based on route ID and state FIPS code. I then applied the spatial join tool on dissolved highway data and monitoring location data to calculate the sum of AADT within 2/5/10/15/20/25 miles of each lead monitoring station³. Note that I also filtered the dissolved highway data where the variable `facility_system` equals 1/2/3/4/5 before spatial join⁴.

3.3 PRISM Climate Data

The PRISM monthly datasets are gridded climate datasets for the conterminous United States. It is produced by the PRISM Climate Group at Oregon State University and has a resolution of 4 km from 1981 onward. I obtained the yearly/monthly mean temperature (°C) and precipitation (mm) for each moni-

²HPMS website: <https://www.fhwa.dot.gov/policyinformation/hpms.cfm>

³For an illustration of the AADT data generating process, please see the appendix.

⁴For variable `facility_system`, 1 stands for interstate highway; 2 stands for principal arterial other freeways and expressways; 3 stands for principal arterials- other; 4 stands for minor arterial; 5 stands for major collector. The reason why I select these types is that these highway segments are required to be reported as full extents by the state DOT.

toring station from 2011-2017 via the Google Earth Engine platform. The below figure shows the descriptive statistics of the major variables.

Table 3.1: Descriptive Statistics

	n	mean	sd	min	max
Lead (ug/L)	29,157	2.97	6.66	3.00E-05	109.00
Total AADT within 2 miles (million)	25,186	0.18	0.74	0	15.97
Total AADT within 5 miles (million)	28,010	0.68	3.20	1.83E-05	56.42
Total AADT within 10 miles (million)	28,793	1.85	7.88	1.00E-05	105.26
Total AADT within 15 miles (million)	28,957	2.98	11.16	1.50E-05	126.98
Total AADT within 20 miles (million)	29,049	4.00	13.62	1.50E-05	140.48
Total AADT within 25 miles (million)	29,076	4.98	15.53	1.50E-05	154.68
Mean precipitation (mm)	28,944	83.23	39.16	3.16	317.15
Mean temperature (°C)	28,944	13.39	5.91	-2.82	26.04

To preliminarily assess the relationship between AADT and lead concentration in water, I regress AADT and lead data separately on the year and monitor fixed effects to get the residuals. The residual plots suggest that there seems to be a positive relationship between AADT and lead contamination in water.

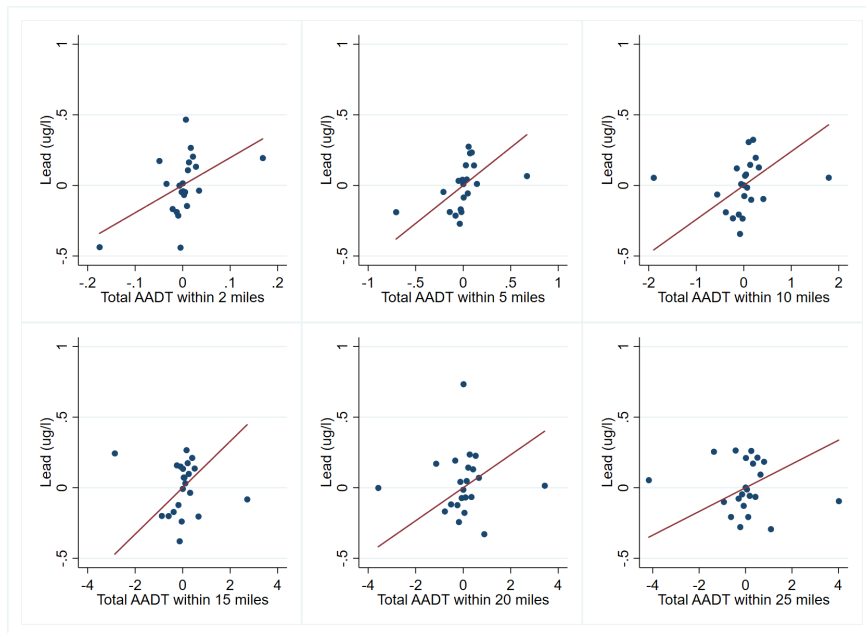


Figure 3.2: Binned Residual Plots for AADT and Lead

CHAPTER 4

EMPIRICAL STRATEGY

The goal of this paper is to capture the effect of highway vehicle traffic on lead concentration in nearby water bodies. The primary challenge is that the monitor-specific characteristics and year-specific shocks may confound the identification. For example, one major challenge for further statistical analysis in previous highway runoff studies was the differences in reporting (Kayhanian et al., 2012). The variability of water quality results is partially due to inconsistent monitoring data as well as inconsistent quality assurance and quality control measures. The monitor-fixed effects could largely alleviate the above problem. To address these issues, I construct a fixed effect model to estimate the effect of AADT on lead in water,

$$WaterQuality_{it} = \beta AADT_{it} + \theta X_{it} + \gamma_t + \delta_i + \epsilon_{it} \quad (4.1)$$

where $WaterQuality_{it}$ is the monitor-level average water quality for lead in year t . $AADT_{it}$ is the sum of AADT within a certain buffer distance from monitor i (distance=2/5/10/15/20/25 miles). X_{it} is a set of weather control variables including mean monthly total precipitation in year t and yearly average temperature. γ_t and δ_i are the year and individual fixed effects. The sample year is from 2011 to 2017.

As mentioned earlier, a considerable amount of rainfall could wash the lead pollutants on the road to nearby surface water, leading to worsening water quality during heavy storm events. Apart from this mobilizing effect, the diluting effect is also found in the previous study (Kayhanian et al., 2003). The diluting effect indicates that higher rainfall intensity will result in lower pollutant concentrations in runoff. To formally test for the two contrasting effects, I utilize the monthly water quality data and run the following regression:

$$WaterQuality_{im} = \beta AADT_{it} + \alpha AADT_{it} * Precip_{im} + \theta Precip_{im} + \gamma_t + \delta_i + \epsilon_{im}. \quad (4.2)$$

Here $WaterQuality_{im}$ is the monitor-level average water quality for lead in month m . $Precip_{im}$ is the monthly total precipitation for monitor i . The coefficient of interest is α . If α is greater than zero, the mobilizing effect dominates. Similarly, if α is less than zero, the diluting effect plays a bigger role. I also include a more flexible model below by adding the interaction of AADT and different precipitation bins.

$$WaterQuality_{im} = \beta AADT_{it} + \sum_{k=1}^8 \alpha_k AADT_{it} * PrecipBin_{imk} + \sum_{k=1}^8 \theta_k PrecipBin_{imk} + \gamma_t + \delta_i + \epsilon_{im}. \quad (4.3)$$

The variables $PrecipBin$ are generated by dividing the monthly total precipitation into nice groups: 0-25, 25-50, 50-75, 75-100, 100-125, 125-150, 150-200, 200-450, and above 450 mm. The interaction terms allow the effect of highway traffic on lead in water to vary with different bins of rainfall. It would be useful to look at which precipitation bin yields the strongest effect and adopt appropriate mitigation measures anticipating that specific storm event. Also, I controlled for the monitor fixed effect δ_i and the year fixed effect γ_t . Except where otherwise noted, all regressions in this paper are clustered by the HUC4¹ watershed.

¹USGS divides the country into 21 regions (HUC2), 222 subregions (HUC4), 370 basins

According to USGS's definition, a watershed is an area of land that drains all the streams and rainfall to a common outlet.

(HUC6), 2,270 subbasins (HUC8), 20,000 watersheds (HUC10), and around 100,000 subwatersheds (HUC12).

CHAPTER 5

RESULTS

5.1 Main Results

5.1.1 Baseline Regressions

The first finding is that highway traffic significantly increases lead pollution in nearby water as is shown in Figure 5.1. The effect gets smaller when the buffer distance increases. This is reasonable since the lead leakage from cars driving further away will less likely to enter the water body.

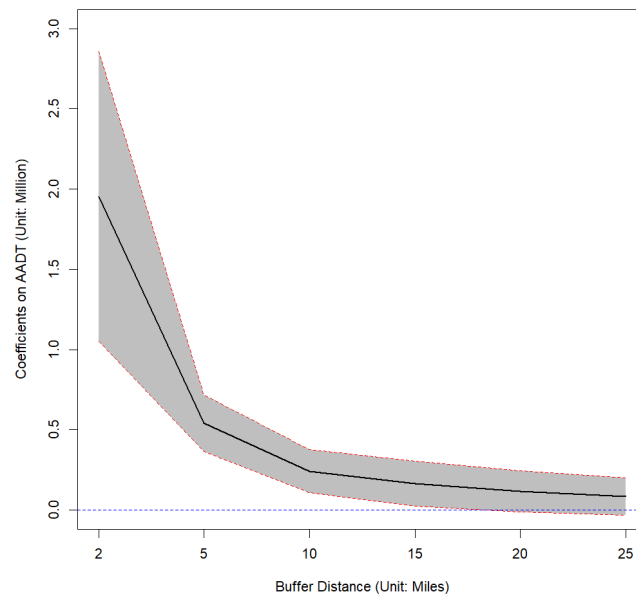


Figure 5.1: Baseline Estimation Result

Note: The black solid line represents the coefficients on AADT from the six regressions based on equation (4.1). The red dotted lines are 90% upper & lower confidence intervals.

Table 5.1 further shows the estimated effect of AADT on lead concentration

using the fixed effects model. Column 1-6 represents different buffer distances. All columns include the monitor and year fixed effects and the standard errors are clustered at the HUC4 watershed level. The baseline results imply that, on average, one million more vehicles within 2 miles are associated with 1.95 ug/L increase in lead concentration in nearby surface water bodies, holding all else equal. The effect decreases as the buffer distance increases- one million more vehicles within 5 miles are associated with 0.54 ug/L increase in lead pollution in water, which is about 1/4 of the effect for 2 miles.

Table 5.1: Baseline Regression Result

	(1)	(2)	(3)	(4)	(5)	(6)
	2 miles	5 miles	10 miles	15 miles	20 miles	25 miles
Dep Var	Lead (ug/L)					
AADT	1.95*** (0.55)	0.54*** (0.11)	0.24*** (0.08)	0.16* (0.09)	0.12 (0.08)	0.08 (0.07)
Mean Precipitation	0.0039 (0.0044)	0.0034 (0.0043)	0.004 (0.0043)	0.0042 (0.0044)	0.0043 (0.0043)	0.0043 (0.0043)
Mean Temperature	0.0091 (0.1454)	0.1066 (0.1550)	0.15 (0.1559)	0.1555 (0.1554)	0.1611 (0.1554)	0.1585 (0.1555)
Monitor FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Cluster	HUC4	HUC4	HUC4	HUC4	HUC4	HUC4
Obs	25,102	27,889	28,648	28,800	28,881	28,905
R2	0.76	0.77	0.77	0.77	0.77	0.77
Within R2	0.003	0.005	0.005	0.004	0.003	0.002

Note: significant codes: 0.01 '***' 0.05 '**' 0.1 '*'

From the sample data, the total AADT within 2 miles of the monitoring stations increases by 0.68 million in 2017 compared with 2011.¹ Hence, the increase in AADT leads to 1.33 ug/L more lead in water, which is about 45%²

¹The number 0.68 is obtained by regressing AADT on the year dummies except 2011 as well as monitor fixed effects and extracting the coefficient on the 2017 dummy.

²The calculations are: $0.68 * 1.95 \approx 1.33$ ug/L; $1.33 / 2.97 \approx 45\%$.

of the mean lead concentration in the water of the US. Even a small portion of lead contamination could lead to serious damage to our health and the nearby ecosystems. Therefore, the relatively large effect of highway traffic on lead in water cannot be neglected.

Considering that the two weather control variables are not significant in the above regression, I introduced quadratic terms of precipitation and temperature.³ Table 5.2 suggests that there seems to be an inverted U-shaped relationship between precipitation and lead concentration. It may happen that there are mobilizing effects followed by diluting effects. Again, there is no significant relationship between temperature and lead in water.

Table 5.2: Regression with Quadratic Weather Terms

	(1)	(2)	(3)	(4)	(5)	(6)
	2 miles	5 miles	10 miles	15 miles	20 miles	25 miles
Dep Var	Lead (ug/L)					
AADT	1.93*** (0.55)	0.54*** (0.11)	0.24*** (0.08)	0.16* (0.08)	0.12 (0.08)	0.08 (0.07)
Mean Precipitation	0.05** (0.02)	0.05** (0.02)	0.05** (0.02)	0.05** (0.02)	0.05** (0.02)	0.05** (0.02)
Mean Precip Squared	-0.0002** (8.66e-5)	-0.0002** (8.76e-5)	-0.0002** (8.81e-5)	-0.0002** (9.01e-5)	-0.0002** (8.99e-5)	-0.0002** (8.97e-5)
Mean Temperature	0.03 (0.27)	0.19 (0.26)	0.25 (0.26)	0.27 (0.27)	0.27 (0.27)	0.27 (0.27)
Mean Temp Squared	0.0018 (0.0120)	-0.0010 (0.0112)	-0.0016 (0.0111)	-0.0021 (0.0113)	-0.0021 (0.0114)	-0.0020 (0.0114)
Monitor FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Cluster	HUC4	HUC4	HUC4	HUC4	HUC4	HUC4
Obs	25,102	27,889	28,648	28,800	28,881	28,905
R2	0.76	0.77	0.77	0.77	0.78	0.77
Within R2	0.005	0.006	0.007	0.006	0.005	0.004

Note: significant codes: 0.01 '***' 0.05 '**' 0.1 '*'

³I also consider the regressions with weather bins in Chapter 5.2 Robustness Checks.

5.1.2 Monthly Regressions

One possible channel of how AADT affects lead concentration in water is that during intense rainfall events, the rain or snow can wash the lead leaked from the vehicle's wheel weights or brake pads to the nearby rivers or lakes. Apart from this mobilizing effect, heavy rainfall may also result in the diluting effect. As there is more water entering the river or lake, the concentration of lead falls. To answer the question of whether the mobilizing effect or the diluting effect dominates, I constructed the model shown in equation (4.2). Table 5.3 illustrates the estimation result.

Table 5.3: Monthly Regression with the Interaction Term

	(1)	(2)	(3)	(4)	(5)	(6)
	2 miles	5 miles	10 miles	15 miles	20 miles	25 miles
Dep Var	Lead (ug/L)					
AADT * Total Precip	0.0075*** (0.0008)	0.0020*** (0.0002)	0.0009*** (0.0001)	0.0006*** (8.34e-5)	0.0005*** (6.96e-5)	0.0005*** (6.21e-5)
AADT	2.807*** (0.9115)	0.7290*** (0.1961)	0.2607* (0.1450)	0.1586 (0.1374)	0.1049 (0.1212)	0.0656 (0.1093)
Total Precipitation	0.0027* (0.0014)	0.0027* (0.0014)	0.0023* (0.0013)	0.002 (0.0014)	0.0018 (0.0014)	0.0016 (0.0013)
Monitor FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Cluster	HUC4	HUC4	HUC4	HUC4	HUC4	HUC4
Obs	62,749	68,587	69,836	70,055	70,158	70,196
R2	0.57	0.58	0.58	0.58	0.58	0.58
Within R2	0.01	0.01	0.01	0.01	0.01	0.01

Note: significant codes: 0.01 '***' 0.05 '**' 0.1 '*'

The coefficients on the interaction term *AADT * TotalPrecip* are all positive and significant, implying that when there is more precipitation, the effect of AADT on lead in water gets larger. This confirms that the mobilizing effects

dominate in the context of the US. I further restrict the sample to rainy months (i.e. May to September) in Table 5.4, the coefficients on $AADT * TotalPrecip$ slightly increase.

Table 5.4: Monthly Regression with the Interaction Term (Rainy Months)

	(1)	(2)	(3)	(4)	(5)	(6)
	2 miles	5 miles	10 miles	15 miles	20 miles	25 miles
Dep Var	Lead (ug/L)					
AADT * Total Precip	0.0100*** (0.0020)	0.0025*** (0.0006)	0.0011*** (0.0003)	0.0008*** (0.0002)	0.0006*** (0.0002)	0.0006*** (0.0001)
AADT	2.925*** (0.9917)	0.7895*** (0.2371)	0.3145* (0.1772)	0.2209 (0.1643)	0.1642 (0.1472)	0.1207 (0.1359)
Total Precipitation	0.0043** (0.0019)	0.0043** (0.0019)	0.0039** (0.0018)	0.0036** (0.0018)	0.0033* (0.0018)	0.0029 (0.0018)
Monitor FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Cluster	HUC4	HUC4	HUC4	HUC4	HUC4	HUC4
Obs	32,656	36,004	36,749	36,879	36,953	36,983
R2	0.60	0.62	0.62	0.62	0.62	0.62
Within R2	0.01	0.02	0.02	0.02	0.02	0.02

Note: significant codes: 0.01 '***' 0.05 '**' 0.1 '*'

It is also interesting to see whether different precipitation bins yield different magnitudes of mobilizing/diluting effects. Moreover, identifying the range of precipitation which brings the largest effect will benefit the country's stormwater management system. Figure 5.2 depicts the results of equation (4.3).⁴ The y axis denotes the coefficients α_k on the interaction terms $AADT_{it} * PrecipBin_{imk}$, which can be interpreted as the relative effect to the 0-25 mm precipitation bin. Generally speaking, the mobilizing effect becomes stronger as there is more rainfall and the mobilizing effect dominates the diluting effect. During heavy rainy months when total precipitation exceeds 450 mm, the mobilizing effect

⁴An alternative approach using wider ranges of precipitation and thus fewer bins is shown in the appendix. The result is also very similar to Figure 5.2.

reaches its maximum value. According to EPA, California DOT and Washington State DOT have already developed related monitoring programs for highway runoff.⁵ The above results suggest that a specialized water quality monitoring program for highway runoff is needed for the whole country. The findings also highlight the importance of performing best management practices (BMP) such as designing vegetated filter strips along highways, creating detention and retention ponds, street sweeping, and preservation of natural vegetation which can reduce the amount of runoff containing pollutants entering the nearby water and mitigate climate change impacts.

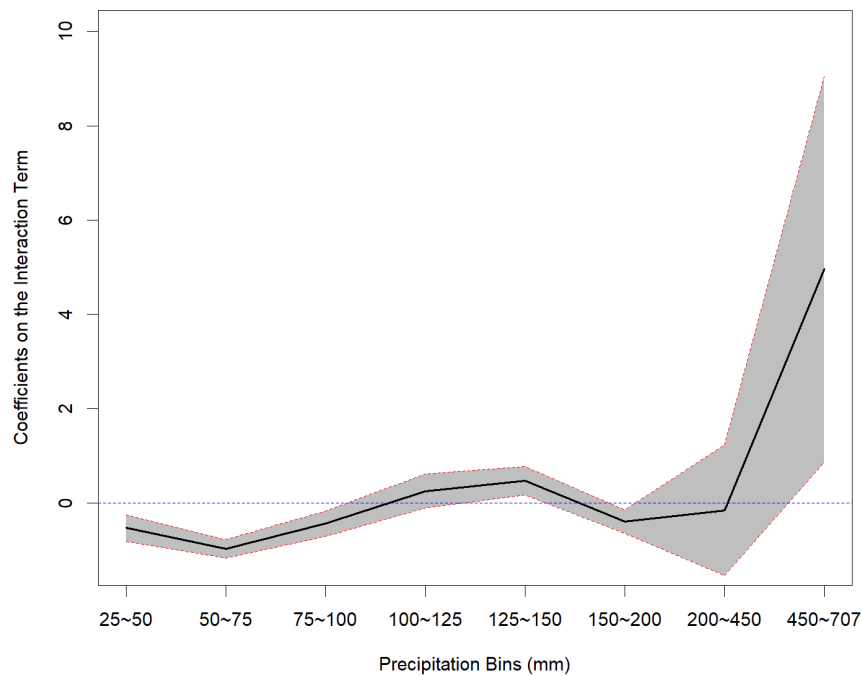


Figure 5.2: Monthly Regressions using Precipitation Bins

Note: The black solid line represents the coefficients on the interaction terms of AADT and eight precipitation bins. The red dotted lines are 90% upper & lower confidence intervals.

⁵EPA's website: <https://www.epa.gov/npdes/stormwater-discharges-transportation-sources-research-tools-and-webcasts>

5.2 Robustness Checks

The local weather conditions especially the rainfall patterns can greatly affect the lead concentration in water. To allow for a more flexible model, I generated a series of indicator variables for 5-degree temperature (F) and 40-mm precipitation separately. In total, there are twelve temperature bins and eight precipitation bins, which is sufficient to capture the nonlinearity between weather and lead in water. Again, the six columns represent different buffer distances and all regressions include year and monitor fixed effects. The coefficients on variable *AADT* are all smaller than those in the baseline model but are still very close in magnitude. For example, column (1) indicates that a million more vehicles on the highway within a 2-mile buffer zone is associated with 1.85 ug/L increase in lead concentration in adjacent surface water, holding all else equal. The significance levels of the estimators are the same as those in the baseline.

Table 5.5: Regression with Weather Bins

	(1)	(2)	(3)	(4)	(5)	(6)
	2 miles	5 miles	10 miles	15 miles	20 miles	25 miles
Dep Var	Lead (ug/L)					
AADT	1.85*** (0.54)	0.52*** (0.11)	0.23*** (0.08)	0.16* (0.09)	0.11 (0.08)	0.08 (0.07)
Precipitation Bins	Yes	Yes	Yes	Yes	Yes	Yes
Temperature Bins	Yes	Yes	Yes	Yes	Yes	Yes
Monitor FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Cluster	HUC4	HUC4	HUC4	HUC4	HUC4	HUC4
Obs	25,102	27,889	28,648	28,800	28,881	28,905
R2	0.76	0.77	0.77	0.77	0.78	0.78
Within R2	0.0085	0.0090	0.0091	0.0085	0.0074	0.0065

Note: significant codes: 0.01 '***' 0.05 '**' 0.1 '*'

Another concern is that yearly specific regional hydrological conditions may

confound the estimation. So, I added the interacted fixed effect for the HUC4 watershed and year. In Table 5.6, the significance levels of the coefficients across six models are all equal to 0.01 while the coefficients on *AADT* decrease sharply for smaller buffer zones. Specifically, the effect of road traffic within 2 miles on lead contamination in water decreases to only one-third of the baseline effect. And the effect of traffic within 5 miles on lead pollution in water is only one-half of the baseline effect. For buffer distances greater than or equal to 10 miles, there is no big change in the coefficient on *AADT* compared with the baseline results.

Table 5.6: Fixed Effects Regression with HUC4 * Year FE

	(1)	(2)	(3)	(4)	(5)	(6)
	2 miles	5 miles	10 miles	15 miles	20 miles	25 miles
Dep Var	Lead (ug/L)					
AADT	0.68*** (0.10)	0.22*** (0.04)	0.13*** (0.02)	0.13*** (0.02)	0.11*** (0.02)	0.09*** (0.02)
Mean Precipitation	0.05*** (0.02)	0.05*** (0.02)	0.05*** (0.02)	0.05*** (0.02)	0.05*** (0.02)	0.05*** (0.02)
Mean Precip Squared	-0.0002*** (7.29e-5)	-0.0002*** (7.69e-5)	-0.0002*** (7.47e-5)	-0.0002*** (7.41e-5)	-0.0002*** (7.39e-5)	-0.0002*** (7.39e-5)
Mean Temperature	-0.13 (0.15)	-0.11 (0.14)	-0.08 (0.13)	-0.07 (0.14)	-0.06 (0.14)	-0.06 (0.14)
Mean Temp Squared	0.0022 (0.0052)	0.0015 (0.0048)	0.0011 (0.0046)	0.0009 (0.0048)	0.0005 (0.0048)	0.0005 (0.0047)
Monitor FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
HUC4 * Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Obs	25,102	27,889	28,648	28,800	28,881	28,905
R2	0.62	0.63	0.63	0.63	0.63	0.63
Within R2	0.01	0.01	0.01	0.01	0.01	0.01

Note: significant codes: 0.01 '***' 0.05 '**' 0.1 '*'

The parsimonious model again confirms the inverted U-shaped relationship between precipitation and lead concentration and the coefficients on the precipitation-related terms are exactly the same as those in the baseline.

As illustrated in Figure 3.1, it is also likely that there exists spatial dependence in lead concentration. This means that nearby water quality monitoring sites tend to have more similar readings in lead concentration than farther ones. To account for the possible spatial clustering, I follow Conley (1999) [30] and compute the Conley standard errors while assuming that monitoring sites within a distance of 8 km are spatially correlated. The significance levels of the coefficients on *AADT* are very close to the baseline regressions with quadratic weather terms. For column (4), the significance level of the coefficients on *AADT* changes from 0.1 to 0.05. For the coefficients on weather control variables, the significance levels stay the same as the baseline.

Table 5.7: Regression with Conley Standard Errors (8km)

	(1)	(2)	(3)	(4)	(5)	(6)
	2 miles	5 miles	10 miles	15 miles	20 miles	25 miles
Dep Var	Lead (ug/L)					
AADT	1.93*** (0.52)	0.53*** (0.18)	0.24*** (0.08)	0.16** (0.08)	0.12 (0.07)	0.08 (0.07)
Mean Precipitation	0.05*** (0.02)	0.05*** (0.02)	0.05*** (0.02)	0.05*** (0.02)	0.05*** (0.02)	0.05*** (0.02)
Mean Precip Squared	-0.0002*** (0.0001)	-0.0002*** (0.0001)	-0.0002*** (0.0001)	-0.0002*** (0.0001)	-0.0002*** (0.0001)	-0.0002*** (0.0001)
Mean Temperature	0.03 (0.25)	0.19 (0.24)	0.25 (0.24)	0.27 (0.24)	0.27 (0.24)	0.27 (0.24)
Mean Temp Squared	0.0018 (0.011)	-0.0010 (0.0099)	-0.0016 (0.0097)	-0.0021 (0.0098)	-0.0021 (0.0099)	-0.0020 (0.0099)
Monitor FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Obs	25,102	27,889	28,648	28,800	28,881	28,905
R2	0.53	0.55	0.55	0.55	0.55	0.55
Within R2	0.00	0.01	0.01	0.01	0.01	0.00

Note: significant codes: 0.01 '***' 0.05 '**' 0.1 '*'

5.3 Extension

The baseline regression tells us that the effect of highway traffic on lead pollution in water decrease as the buffer distance increases. One may also wonder which part of the buffer zone produces the strongest effect. I separate the buffer zone to five rings: 0-5, 5-10, 10-15, 15-20, and 20-25 miles and run the following spatial lag model,

$$WaterQuality_{it} = \sum_{\tau=1}^5 \beta_{\tau} * AADT_{it\tau} + \theta X_{it} + \gamma_t + \delta_i + \mu_{ht} + \epsilon_{it}. \tag{5.1}$$

where $AADT_{it\tau}$ is the total AADT within ring τ of monitoring site i in year t . μ_{ht} is the HUC4-year interacted fixed effect. X_{it} is a vector of quadratic weather terms.

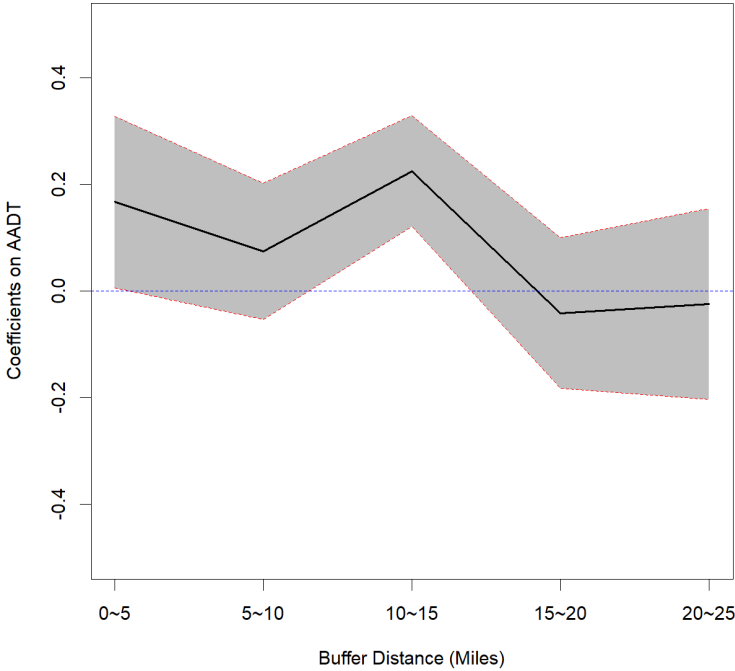


Figure 5.3: Ring-like Estimation Result

Note: The black solid line represents the coefficients on AADT of five rings. The red dotted lines are 90% upper & lower confidence intervals.

Figure 5.3 shows that vehicles driving 10-15 miles away from the water quality monitoring sites have the strongest negative effect on lead pollution in water. On average, one million more vehicles on the 10-15 mile ring will result in 0.23 ug/L increase in lead concentration in water, holding all else constant. The second largest effect is brought by cars driving 0-5 miles from the monitoring site. However, for the last two rings, there is no significant effect of AADT on lead pollution in water.

Table 5.8: Ring-like Regression

Dep Var	Lead (ug/L)
AADT within 0-5 mile	0.17* (0.10)
AADT within 5-10 mile	0.07 (0.08)
AADT within 10-15 mile	0.23*** (0.06)
AADT within 15-20 mile	-0.04 (0.09)
AADT within 20-25 mile	-0.02 (0.11)
Mean Precipitation	0.05*** (0.02)
Mean Precipitation Squared	-0.0002*** (7.63e-5)
Mean Temperature	-0.11 (0.14)
Mean Temperature Squared	0.001 (0.0049)
Monitor FE	Yes
Year FE	Yes
HUC4 * Year FE	Yes
Cluster	HUC4
Obs	27,889
R2	0.63
Within R2	0.01

Note: significant codes: 0.01 '***' 0.05 '**' 0.1 '*'

5.4 Heterogeneity

Previous engineering studies suggest that highway runoff concentrations are typically higher in urban areas than rural areas (Kayhanian et al., 2003; Gan et al., 2008 [31]). The effect of AADT on lead concentration in water may also differ in urban and rural areas. I classify a monitoring site as "Urban" if the site is located within the boundary of the 2010 Census Urban Area. If the site is out of the boundary, it is classified as "Rural". Column (1) & (2) of Table 5.9 shows the results obtained by regressing the lead concentration on total AADT within 2 miles for urban and rural areas, separately. The coefficients on AADT in column (2) are bigger than that in column (1), suggesting that the effect is stronger in rural areas compared with urban areas.

Table 5.9: Urban VS Rural

	(1)	(2)	(3)	(4)
	Urban 2 miles	Rural 2 miles	Urban 5 miles	Rural 5 miles
Dep Var	Lead (ug/L)			
AADT	1.90*** (0.23)	2.18*** (0.51)	0.53*** (0.03)	0.58*** (0.09)
Mean Precipitation	0.04*** (0.01)	0.05** (0.03)	0.04*** (0.01)	0.05** (0.03)
Mean Precip Squared	-0.0002*** (5.6e-5)	-0.0002** (0.0001)	-0.0002*** (5.25e-5)	-0.0002** (0.0001)
Mean Temperature	0.6 (0.68)	-0.14 (0.30)	0.57 (0.64)	0.11 (0.30)
Mean Temp Squared	-0.03 (0.04)	0.01 (0.01)	-0.03 (0.04)	0.01 (0.01)
Monitor FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Obs	6,374	18,728	6,382	21,507
R2	0.75	0.76	0.75	0.77
Within R2	0.02	0.00	0.02	0.00

Note: significant codes: 0.01 '***' 0.05 '**' 0.1 '*'

Similarly, when I include the AADT generated using the 5-mile buffer zone in the last two columns, the coefficients on AADT for the urban sample is bigger than that for the rural sample. One explanation is that the portion of heavy duty trucks driving on rural highways is larger than urban roads. Since heavy duty trucks usually have more emissions (Lough et al., 2005), the effect of AADT on lead in water is greater in rural areas.

CHAPTER 6

CONCLUSION

Lead pollution causes great damage to the health of both humans and the ecosystem. Up to now, a substantial amount of lead is consistently brought by the transportation sector through on-road vehicles and keeps contaminating the water of the United States. To my knowledge, this paper is the first nationwide empirical study to estimate the effect of highway traffic on lead concentration in water. The main result shows that, on average, one million more cars within 2 miles of the water are associated with 1.95 ug/L increase in lead contamination in the surface water, holding all else equal. The effect is relatively local as it decreases when the buffer zones get wider. The estimated effect has both statistical and economic significance. Over the seven years from 2011-2017, the increase in lead in water due to heavier highway traffic amounts to 1.33 ug/L, accounting for about 45 % of the mean lead concentration in the surface water of the US.

This paper is also the first to empirically test the mobilizing and diluting effects which are often referred to in former engineering studies. I find that the effect of traffic on nearby lead pollution in water gets stronger during heavy rainy months, which is aligned with the mobilizing effect. Moreover, the effect becomes the strongest when the monthly total precipitation exceeds 450 mm. The findings highlight the urgent need to establish a national monitoring system for highway runoff and the need to adopt site-specific mitigation measures for climate change as well as increasing extreme storm events.

The above results are robust across a series of specifications. In addition, I find that vehicles driving on rings within 10-15 miles of the water yield the largest negative effect on lead pollution. The second largest effect is brought

by cars on the rings within 0-5 miles. Also, related authorities should pay special attention to heavy duty trucks that emit more pollutants than most other vehicles. This is evidenced earlier that the effect of highway traffic on lead contamination in water is larger in rural areas compared to urban areas.

There are several policy implications based on my findings. First, source controls could be taken on to alleviate the adverse effect on water quality due to the increasing traffic volume. For example, enforcing EPA's two initiatives- National Lead Free Wheel Weight Initiative & Copper-Free Brake Initiative to become laws may improve the water quality in the US. Second, establishing a nationwide specialized monitoring system for highway runoff could lead to better performance of best management practices (BMPs). Third, site-specific mitigation measures like designing vegetated filter strips along highways, creating detention and retention ponds, street sweeping, and preservation of natural vegetation could be used more often by the local government.

APPENDIX A

PICTURES OF WHEEL WEIGHTS AND BRAKE PADS



Figure A.1: Wheel Weights

Source: <https://www.scooterwest.com/wheel-weights-12-squares-black-ww-bk.html>



Figure A.2: Brake Pads

Source: <https://www.istockphoto.com/photo/mechanics-hands-displaying-worn-and-new-brake-pads-gm184974687-18785559>

APPENDIX C

THE TREND OF AADT AND LEAD CONCENTRATION

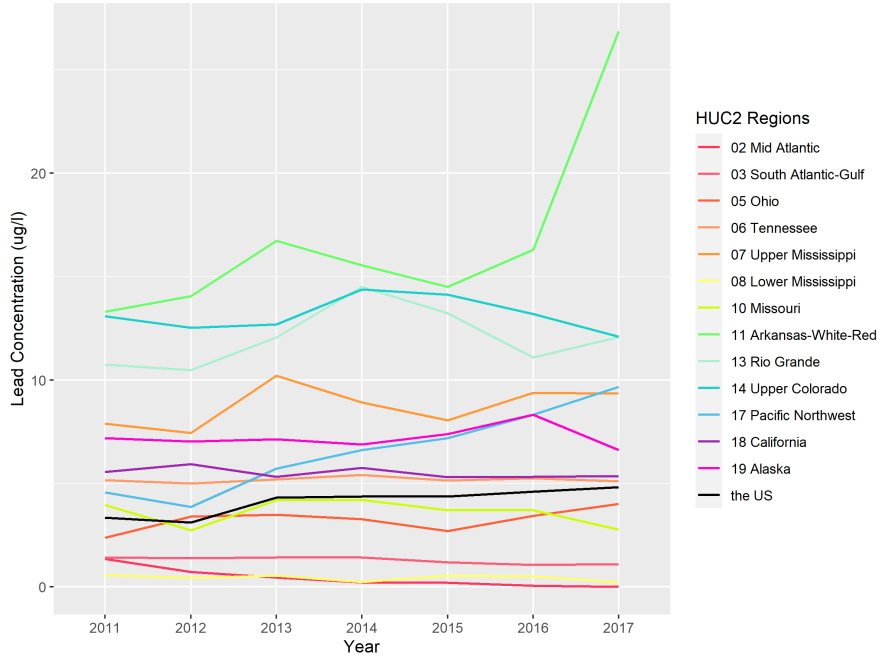


Figure C.1: Lead Concentration (ug/L) Trend for HUC2

Note: The plot is generated by regressing the lead concentration on the year dummies and the monitor fixed effects for different HUC2 samples. The y-axis values are the coefficients on the year dummies plus the mean value of the fixed effects.

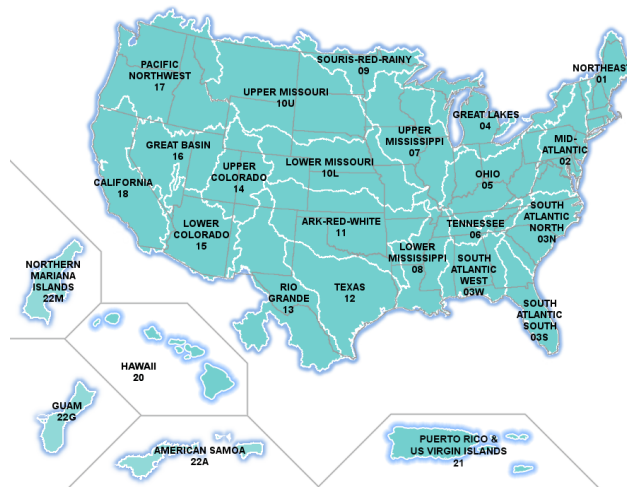


Figure C.2: HUC2 Map

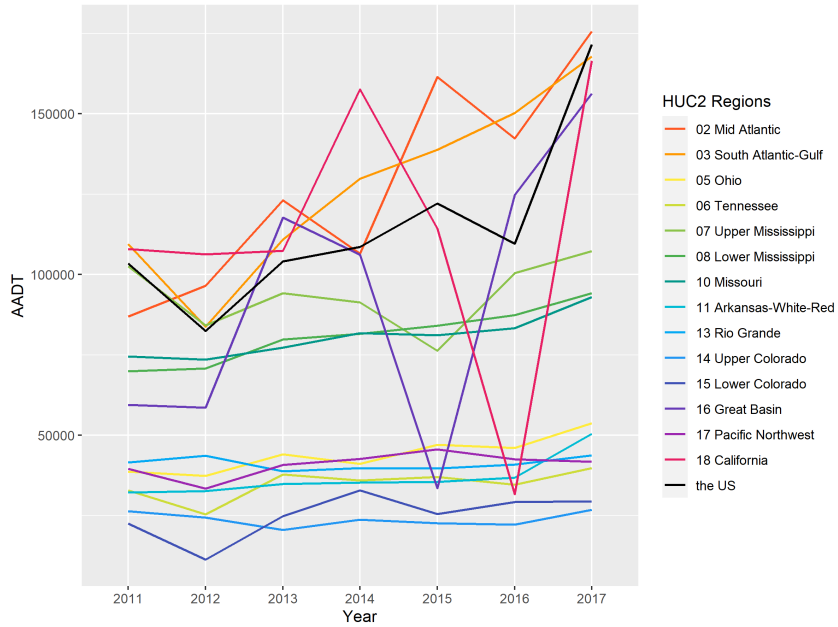


Figure C.3: AADT Trend (2 Miles) for HUC2

Note: The plot is generated by regressing AADT on the year dummies and the monitor fixed effects for different HUC2 samples. The y-axis values are the coefficients on the year dummies plus the mean value of the fixed effects.

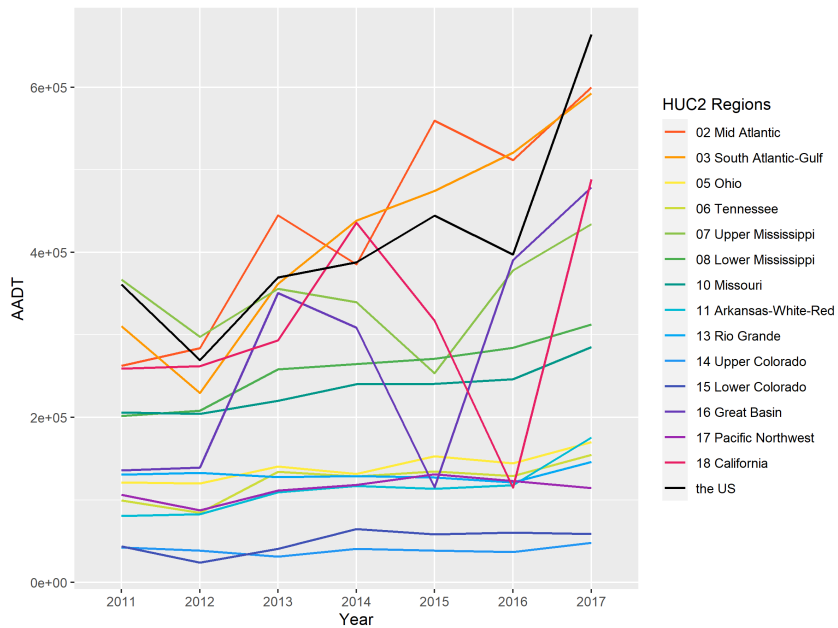


Figure C.4: AADT Trend (5 Miles) for HUC2

Note: The plot is generated by regressing AADT on the year dummies and the monitor fixed effects for different HUC2 samples. The y-axis values are the coefficients on the year dummies plus the mean value of the fixed effects.

APPENDIX D
MONTHLY REGRESSIONS USING ALTERNATIVE PRECIPITATION
BINS

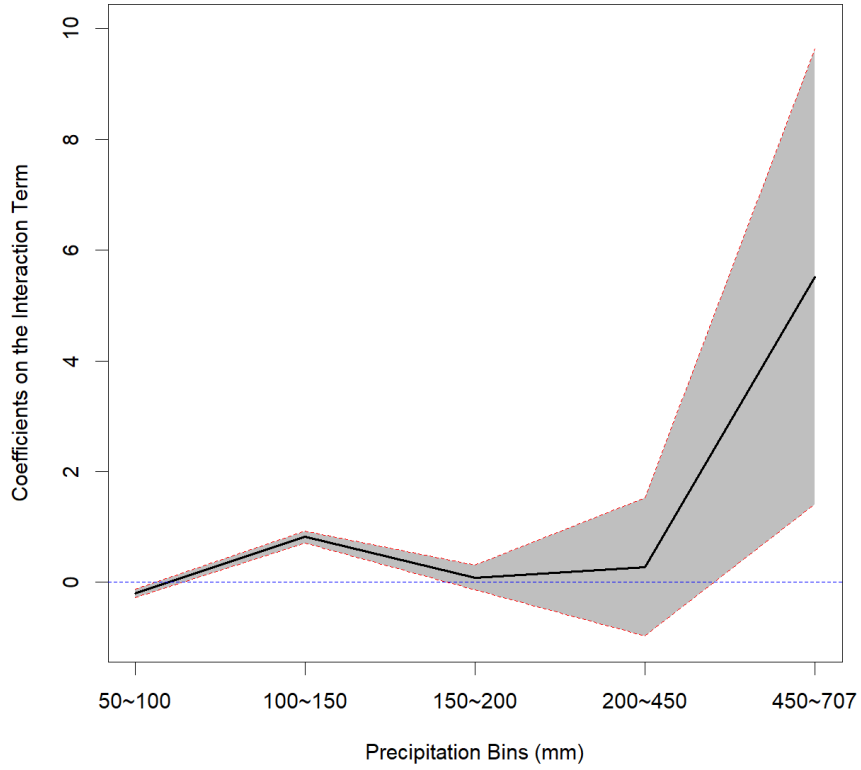


Figure D.1: Monthly Regressions using Alternative Precipitation Bins

Note: The black solid line represents the coefficients on the interaction terms of AADT and five precipitation bins. The red dotted lines are 90% upper & lower confidence intervals.

APPENDIX E
EXAMPLES OF MITIGATION MEASURES



Figure E.1: Vegetated Filter Strips



Figure E.2: Infiltration Pond along SR 510 in Thurston County

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