**Title**

# Estimating Mortality Impacts From Vehicle Emission Reduction Efforts: the Tune In and Tune Up Program in the San Joaquin Valley



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# Estimating Mortality Impacts From Vehicle Emission Reduction Efforts: the Tune In and Tune Up Program in the San Joaquin Valley

A thesis submitted in partial satisfaction

of the requirements for the degree Master of Science

in Environmental Health Sciences

by

Rachel Emma Connolly

2018

ABSTRACT OF THE THESIS

Estimating Mortality Impacts From Vehicle Emission Reduction Efforts: the Tune In and Tune Up Program in the San Joaquin Valley

by

Rachel Emma Connolly

Master of Science in Environmental Health Sciences

University of California, Los Angeles, 2018

Professor Yifang Zhu, Chair

As a response to the poor air quality and associated environmental justice concerns in the San Joaquin Valley region in California, the Tune In & Tune Up (TI&TU) program provides residents with free vehicle emissions testing and vouchers for smog repair. We use data on approximately 17,000 repaired TI&TU vehicles from 2012-2017 to quantify the nitrogen oxides ($NO_X$) emissions prevented from the program and calculate resulting mortality impacts from reduced exposure to fine particulate matter ($PM_{2.5}$) in the form of secondary nitrates. After applying a novel smog repair emissions abatement depreciation function, we find that five and a half years of operation of the TI&TU program will have reduced $NO_X$ emissions by 149 tons through the end of 2018. Using a concentration response function for ambient $PM_{2.5}$, we find that .24 premature deaths will have also been avoided. In future work, we will use these findings to evaluate the program's relative cost-effectiveness as well as build on these results to assess morbidity and livelihood impacts.

The thesis of Rachel Emma Connolly is approved.

Michael Jerrett

R. Jisung Park

Yifang Zhu, Committee Chair

University of California, Los Angeles

2018

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## 1. Introduction

### 1.1 Vehicle Emissions and Health

Outdoor air pollution in the United States is a longstanding environmental health concern (Kampa & Castanas, 2008). Motor vehicle emissions contribute to greenhouse gas emissions and smog formation (California Air Resources Board, 2018b; Faiz, Weaver, & Walsh, 1996). Though the United States vehicle fleet is significantly cleaner than it was 30 years ago (US EPA, 2018a), and California has more stringent emission standards than the US EPA (US EPA, 2018c), transportation is still the largest source of smog formation in California (California Air Resources Board, 2018b).

Vehicle exhaust primarily contains oxides of nitrogen ($NO_X$), carbon monoxide (CO), hydrocarbons (HC), and particulates (Brugge, Durant, & Rioux, 2007; Westerholm & Egebäck, 1994). $NO_X$ gases predominantly consist of nitrogen dioxide ($NO_2$) and nitric oxide (NO). The majority of $NO_X$ released from mobile sources is NO, which is then oxidized to increase levels of $NO_2$ (Kampa & Castanas, 2008; Olsen, Kohls, & Arney, 2010). Some of the $NO_X$ is transformed into nitrate, which composes approximately 40% of particulate matter (PM), though levels vary based on region and season (California Air Resources Board, 2016). $NO_X$ is released in other fossil fuel burning and manufacturing processes as well, and exposure to $NO_X$ causes respiratory irritation and damage (Agency for Toxic Substances and Disease Registry, 2002; Kagawa, 1985). California-based research indicates that $NO_2$, a component of $NO_X$, is associated with premature death (Jerrett et al., 2013) and a recent study found a 10% decrease in $NO_X$ reduces mortality by .04% (Deschênes, Greenstone, & Shapiro, 2017). A meta-analysis from 2014 found long-term relative risks for a $10\mu g/m^3$ increase to be 1.04, or 4% higher than baseline, and 1.05 for $NO_2$ and fine particulate matter ($PM_{2.5}$), respectively (Faustini, Rapp, & Forastiere, 2014).

Related mortality varies regionally, but a study focused on California found that the single pollutant relative all-cause mortality risk for the interquartile range of exposure to $PM_{2.5}$ (5.3037 $\mu g/m^3$) is 1.032, and is 1.031 for $NO_2$ (4.1167 ppb) (Jerrett et al., 2013).

Though recent research indicates that chronic exposure to $NO_X$ may have an independent impact on health, our analysis focuses on the health impacts from $NO_X$ converted to $PM_{2.5}$ after emission, since the concentration-response relationship between particulate matter and mortality is highly researched and well established. $PM_{2.5}$ is primarily developed through combustion processes, and is known to impact health in various ways. $PM_{2.5}$ is able to enter the human body and travel deep into the lungs, reaching the alveolar region and impairing lung function (Brunekreef & Holgate, 2002; Pope & Dockery, 2006; Xing, Xu, Shi, & Lian, 2016). There is strong scientific evidence indicating that $PM_{2.5}$ pollution adversely impacts cardiovascular and respiratory health through a variety of potential pathways (Anderson, Thundiyil, & Stolbach, 2012; Pope & Dockery, 2006).

Many epidemiological studies have found associations with both long and short term $PM_{2.5}$ exposures and various indicators of health (Brunekreef & Holgate, 2002; Krewski et al., 2009; Pope & Dockery, 2006). The 2018 State of the Global Air report produced by the Health Effects Institute found ambient PM exposure to be the 6$^{th}$ leading cause of premature death globally, following high blood pressure, smoking, and several other lifestyle related causes (Health Effects Institute, 2018) and one study found ambient PM pollution to be the 9$^{th}$ leading risk factor for the global disease burden as of 2010 (Lim et al., 2012). Many studies have quantified global and local mortality due to particulate matter exposure; for example, a study based on the 2010 Global Burden of Disease estimated that ambient PM pollution resulted in approximately 3.1 million deaths and 3.1% of all disability adjusted life years in 2010 (Lim et al., 2012).

### 1.2 The San Joaquin Valley: Transportation, Air Quality, and Environmental Justice

Vehicle emissions are a pressing environmental issue in the San Joaquin Valley (SJV), a region in California with two major freeways which contribute substantially to air pollution in the region (US EPA, 2017b). The SJV is comprised of 8 counties: Fresno, Kern, Kings, Madera, Merced, San Joaquin, Stanislaus, and Tulare. These counties house approximately 4 million residents, and have a higher proportion of minority and low income residents than the state as a whole (US Census Bureau, 2017). The median household income in the SJV is $46,713 as compared to California's $61,818, and the mean income is more than $20,000 lower for the SJV than the state as a whole (US Census Bureau, 2017). The California Office of Environmental Health Hazard Assessment's CalEnviroScreen environmental justice screening tool, which accounts for population characteristics and pollution burden, shows the average percentile for SJV census tracts to be 72.5 (higher percentiles indicate a region is more burdened – 50 is the statewide average), and seven out of the ten tracts with the highest scores in the state are in the SJV (OEHHA, 2017). The vulnerability of the region is illustrated in Figure 1 below, depicting the CalEnviroScreen percentiles for the entire state, with the SJV outlined.

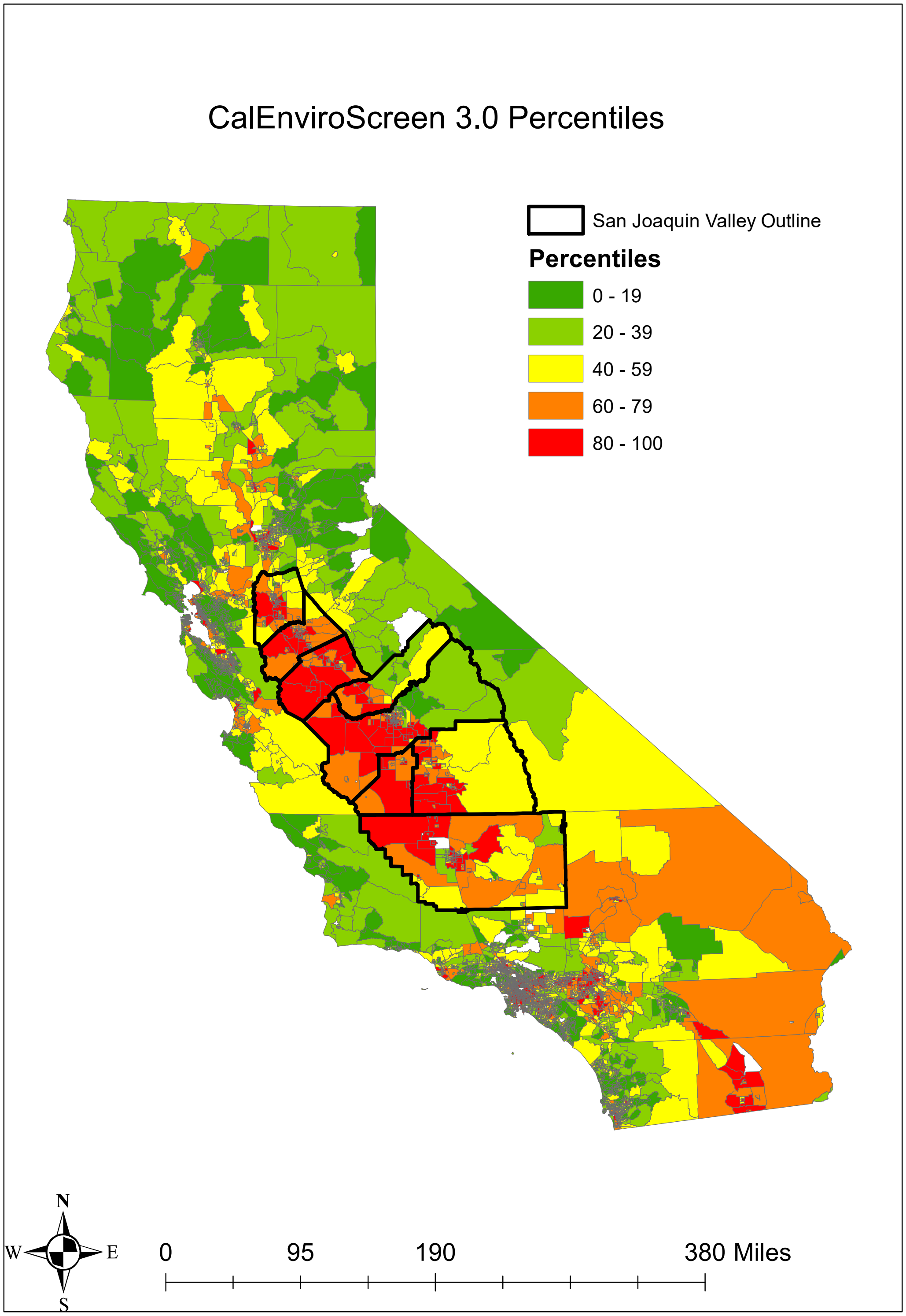


***Figure 1.*** *CalEnviroScreen 3.0 Percentiles, illustrating the environmental justice concerns in the San Joaquin Valley region. Higher percentiles indicate a region has a higher pollution burden and more vulnerable population characteristics (Source: OEHHA, 2017).*

Air quality in the San Joaquin Valley is historically poor, and the region is not compliant with federal standards for ozone and PM (US EPA, 2017e). The impact of poor air quality on health is well-established, not only generally, but in the SJV region specifically. One study found an association between the number of asthma-related symptomatic events for asthmatics and the ambient PM and ozone levels in the region, indicating that individuals with asthma living in the most polluted areas of the SJV are more at risk for related health impacts (Meng et al., 2010). A 2006 report estimated that if the Valley met $PM_{2.5}$ and ozone standards, the region would save approximately $1,000 per person per year, and avoid 460 premature deaths (Hall, Brajer, & Lurmann, 2006). The magnitude of this finding highlights that any comprehensive evaluation of benefits and cost-effectiveness of air pollution policies or programs, in this region and elsewhere, should incorporate health impacts. For all of the aforementioned reasons, the SJV Air Pollution Control District (SJVAPCD) and California Air Resources Board (CARB) have been collaborating for many years to improve the air quality in the SJV air basin, and to ensure that the region has plans in place to meet federal standards.

There is also a higher percentage of commuters using light-duty vehicles in the SJV than in the state overall (US Census Bureau, 2017). There are several methods for transportation in the SJV that reduce the need for single-rider vehicles, such as vanpools, carpools, and public transit options, but these options are often limited. Public transit exists in the Valley, but using it is infeasible for many individuals because of the limitations of the transit system (Margonelli, 2014), and due to the rural nature and population density of the SJV, building out public transit would be challenging (Pierce & Connolly, 2018). A recent report highlights that additional support is necessary for various transportation programs to expand within the Valley, and that policymakers should support these endeavors (Margonelli, 2014).

1.3 California Vehicle Emission Reduction Initiatives and the Tune In & Tune Up Program

Vehicle emission reduction initiatives can support several environmental, economic, and equity objectives, including improvements to local air quality and public health, an equitable distribution of benefits, and the lessening of climate change impacts from reduced greenhouse gas emissions. While these motivations are intertwined, it is often challenging to design a program or policy that maximizes achievement of each objective. We will explore this further below.

Over the past several decades, a multitude of programs incentivizing vehicle repair, retirement, or replacement have emerged in the United States, each of which offer a form of incentive to households as motivation for participation. There are several types of programs operating solely in California focused on reducing emissions from light-duty vehicles, with distributional equity goals incorporated into program design in various ways, including income caps for participation. Though not a permanent solution to the persistent issue of vehicle-associated air pollutant emissions, these programs aim to provide a temporary solution to an environmental issue afflicting regions throughout the state, including the SJV.

One government-run program is the California Consumer Assistance Program (CAP), managed by the Bureau of Automotive Repair (BAR). The CAP program has two participation options: repair assistance for vehicles that have failed smog checks, or vehicle retirement. For an individual to be eligible for a repair and to receive the highest level of compensation for vehicle retirement, their income must be less than or equal to 225% of the federal poverty line (California Bureau of Automotive Repair, 2017). This program is still operating, and a 2015-2016 annual report indicates that 85% of participants in that particular year qualified for the income eligible option.

The California Clean Vehicle Rebate Project (CVRP), funded by a portion of California's cap and trade program and operated by the Center for Sustainable Energy and CARB, provides rebates to California residents for the purchase of clean vehicles; as of 2018, CVRP had provided over 200,000 rebates (Center for Sustainable Energy, 2018). This program was evaluated as a case study, and one notable finding was that "census tracts with lower median household incomes and higher proportions of people of color received fewer clean vehicle rebates," though when controlling for income, otherwise environmentally and socially disadvantaged communities did receive more rebates (Rubin & St-Louis, 2016). Additionally, 83% of program participants had an income of $100,000 or higher. Thus, the authors highlighted the findings of DeShazo et al. of the importance of income caps in these programs (DeShazo, Sheldon, & Carson, 2015). However, we can also note that SB 535 (Greenhouse Gas Reduction Fund, 2012) required that 10% of CVRP funding be used for disadvantaged communities, and SB 1275 (Charge Ahead California, 2014) set an income threshold for participation. The aforementioned analysis was done before the adjustment. This example illustrates how equity can fall through the cracks when a direct effort for inclusion is not made, even when clean vehicles are still being put on the roads, and certain environmental goals are still met.

The San Joaquin Valley's vulnerable population, vehicle dependency and subsequent high levels of mobile source emissions influenced the nonprofit organization Valley Clean Air Now (Valley CAN) to develop and implement the Tune In and Tune Up (TI&TU) smog repair program in 2005. California's smog check program requires the majority of vehicles with a model year of 1976 or later to pass an emissions test before car owners are able to register their vehicles (CA DMV, 2018), which presents a substantial barrier to registration for owners who are not able to pay for smog repairs. TI&TU operates in the SJV, is funded by the SJVAPCD (enhanced vehicle registration fees), and provides free emissions testing and vouchers for smog repair for Valley residents. TI&TU's program design reduces or removes many of the barriers to participation (faced by low-income households) that may be present in other vehicle emission reduction programs, and is potentially the first program in California to implement a grassroots approach to providing underserved households with vehicle assistance (Pierce & Connolly, 2018).

A recently released report evaluates the efficacy, distributional equity, and environmental impact of TI&TU, finding that TI&TU successfully distributed various benefits to the most disadvantaged areas of the region, and of the state (Pierce & Connolly, 2018). From July 2012 – April 2017, TI&TU distributed over $12 million in smog repair vouchers, which resulted in approximate annual emission reductions of 635,000 pounds (315 tons) of HC, CO, and $NO_X$ , and total reductions of 3,800,000 pounds (1,900 tons) over the entire study period (Pierce & Connolly, 2018).[1]

1.4 Research Objectives and Overview

A thorough evaluation of the TI&TU program's benefits and cost-effectiveness should include an assessment of the health impacts due to these pollutant emission reductions. Thus, the primary objectives of the study were 1) to quantify $NO_X$ emission reductions resulting from TI&TU repairs, and 2) to produce a preliminary assessment of mortality impacts.

We calculated total $NO_X$ emission reductions, using a step function to account for repair depreciation. We then converted these values to $PM_{2.5}$ reductions, and used a well-established concentration response function to quantify the health impacts resulting from five and a half

[1] These calculations assume a linear depreciation of the abatement provided by vehicle repairs, described in section 2.2 and based on findings from a recent study on the efficacy of smog repairs (Mérel, Smith, Williams, & Wimberger, 2014).

years of operation of the TI&TU program. We found that 149 tons of $NO_X$ will have been reduced, and .24 premature deaths avoided, through 2018.

This study is at the nexus of air quality, transportation policy, health, and environmental justice, and makes several contributions to the field. Notably, based on an extensive literature search, no other studies on vehicle emission reduction programs have evaluated benefits in terms of mortality impacts. This is also the first study to utilize California-based research on the efficacy of smog repairs to estimate diminishing emission reductions in the years post-repair (Mérel, Smith, Williams, & Wimberger, 2014)

The remaining sections of the paper are organized as follows: Section 2 describes the data sources and empirical methodology of the project, Section 3 presents the estimation results and sensitivity analyses, Section 4 discusses the findings and limitations of this research, and Section 5 concludes.

## 2. Methodology

### 2.1 Data Sources, Extraction and Management

#### *2.1.1 TI&TU Vehicle Emission Reductions*

Of approximately 50,000 vehicles which entered the TI&TU program during the time period of July 2012-December 2017, 20,000 were inspected or repaired at a smog shop, and approximately 17,000 vehicle data entries had all of the vehicle information and emission measurements necessary to complete emission reduction calculations; these are the vehicles we used for our analysis. The TI&TU program and emissions data were extracted from Valley CAN's Salesforce database. Due to the nature of Salesforce's platform, different pieces of data were located in different datasets; the data were joined together in RStudio using various keys provided to us by Valley CAN's external Salesforce consultant. The resulting joined data linked each vehicle with a particular census tract and details on the vehicle's annual emission reduction, among other observations. Annual emission reductions for each vehicle were calculated by Valley CAN and Dr. Jeffrey Williams of UC Davis, using pre- and post-repair emission measurements and various vehicle characteristics, prior to our extraction of the data. This method of estimating emission reductions is described in a CARB report. The formula used for converting pre- and post-repair emission measurements to Federal Test Procedure (grams/mile, or FTP) was also used in a paper conducting analysis on smog repair efficacy (California Air Resources Board, 2008; Mérel et al. 2014). To validate the data used, we confirmed that average $NO_X$ FTP values for the California vehicle fleet are comparable to the FTP values used in our calculations (California Air Resources Board, 2013). All of the data was cleaned and erroneous data (due to manual data entry) were removed.[2]

*2.1.2 San Joaquin Valley $NO_X$ Emission Inventory*

Data on mobile source $NO_X$ emissions in the San Joaquin Valley during the years of 2012-2017 were extracted from CARB's Emission Factors (EMFAC) database (California Air Resources Board, 2018a).

*2.1.3 Ambient $PM_{2.5}$ Levels*

The SJVAPCD provided the research team with modeled and gridded baseline $PM_{2.5}$ estimates for the years of 2012-2016 (SJVAPCD, 2017), which were aggregated to the county level using US Census Bureau data and ESRI's Arc Geographic Information Systems. Since

[2] The following data were removed from our Salesforce dataset: all entries without emission reduction calculations completed; duplicate entries, due to database errors; vehicle entries listed as having completed an accelerated simulation mode (ASM) test with a vehicle weight outside of the realm of possibility (< 1000 or > 9000 pounds), since this could have skewed the emission reduction calculation (not applicable for the smaller number of vehicles with a two-speed idle (TSI) test, since the vehicle weight is not included in the emission reduction calculation); and all entries of vehicles from outside of the San Joaquin Valley.

2017 values were not yet calculated at the time of project initiation, 2016 values were used in our analysis as a substitute. The average annual $PM_{2.5}$ values for the neighborhoods over the entire study period are shown in Figure 2 below.

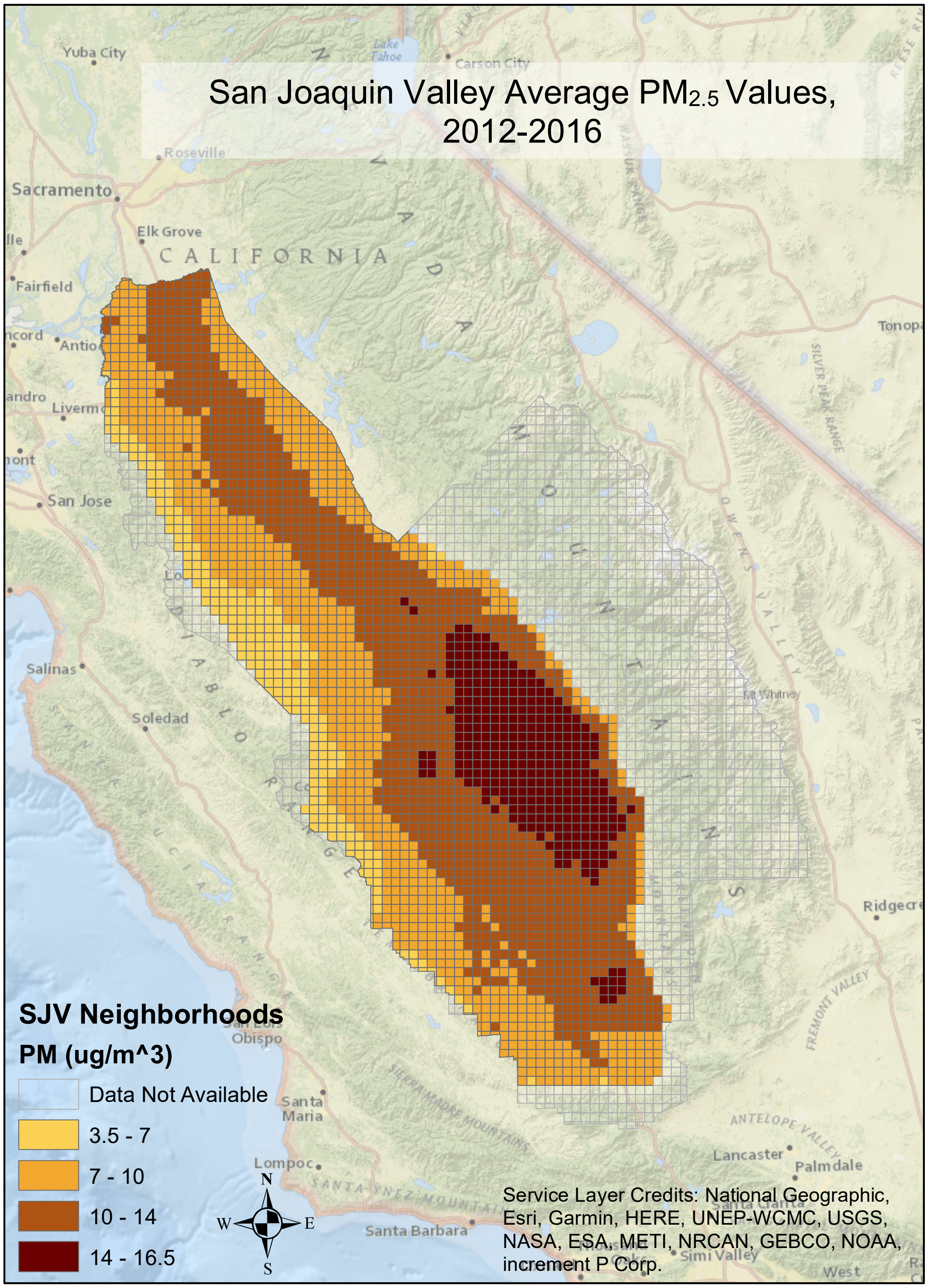


***Figure 2.*** *$PM_{2.5}$ values in SJV neighborhoods, averaged over 2012-2016 (Source: SJVAPCD $PM_{2.5}$ Data)*

*2.1.4 Mortality Rates*

Baseline premature death estimates (2013-2015) for each SJV county were sourced from the Centers for Disease Control and Prevention Wide-ranging Online Data for Epidemiologic Research (CDC WONDER) Underlying Cause of Death dataset, and extracted from the County Health Rankings website (University of Wisconsin Population Health Institute & Robert Wood Johnson Foundation, 2017).

*2.1.5 Population Estimates*

Population estimates were retrieved from the American Community Survey 2015 5-year estimates (US Census Bureau, 2017).

2.2 Calculating $NO_X$ Emission Reductions

The emissions abatement from smog repairs is known to decrease over time (Mérel et al., 2014), so the annual reductions described in Section 2.1.1 are an overestimate, particularly in the years subsequent to repair. To resolve this issue, we applied a depreciation value[3] to these annual values using a step function (i.e., piece-wise constant function) based on results from a study on smog repair efficacy in California (Mérel et al., 2014). This is a novel technique for accounting for repair depreciation; in our literature review, we did not find any other studies which applied this type of function. Additionally, the $NO_X$ reduction values for the small percentage (6%) of vehicles which received a two-speed idle (TSI) test instead of an acceleration simulation mode (ASM) test were calculated using a less reliable method for estimation; since $NO_X$ is not

[3] The decision to use a repair depreciation function was based on Mérel et al.'s findings from a study investigating the efficacy of smog repairs as an emissions abatement tool; they found that 41% of the benefits of abatement (HC, CO, and $NO_X$) were lost within a two year period post-repair (Mérel et al., 2014). They studied vehicles from the California BAR's Consumer Assistance Program, so the sample they used is comparable to TI&TU's participating vehicles. Though we are not able to confirm that the TI&TU vehicles received the same quality of repairs, or will respond to repairs in the exact same way, Mérel's research was the most accurate and comparable resource available for us to apply to our data. Since we are looking solely at $NO_X$ in this study, and upon recommendation from the first author, Pierre Mérel, we used results from one of their alternate models which found that approximately 51% of the abatement for $NO_X$ had diminished two years post-repair.

measured during TSI tests, this adds a layer of uncertainty. We summarized the data to look for significant differences between the reduction values for the two types of tests, and the average reductions for TSI-tested vehicles were six times the average reductions for ASM-tested vehicles. Since the average model year and odometer reading are similar for the two groupings,[4] indicating the vehicle fleets are comparable, we have no reason to believe the reductions should be this significantly different. Due to this uncertainty, the values for the 6% of vehicles that were TSI-tested were replaced with the average reduction value for ASM-tested vehicles.

2.3 Converting $NO_X$ Emission Reductions to Particulate Matter

The methods for this project described here (Section 2.3) and in Section 2.4 were drawn from a recently published study evaluating the adverse health impacts of the Volkswagen emission scandal of 2015 (Wang, Jerrett, Sinsheimer, & Zhu, 2016).

Nitrogen oxides transform into various species after release into the atmosphere. A typical $NO_X$ conversion rate into the secondary nitrates that contribute to fine particulate matter increases is 0.4 , which is the value we used in this study (California Air Resources Board, 2005; Wang et al., 2016). $NO_X$ annual emission reduction values for each TI&TU vehicle were converted into particulate matter changes using equation 1 below.

$$\Delta PM_{2.5\ ij} = PM_{2.5\ ij} * \ k \ * \frac{\Delta NOx_{ij}}{NOx_{ij}} \qquad (1)$$

In equation 1 above, *i* represents the year, *j* represents the area of analysis (county), and *k* is the aforementioned conversion rate for $NO_x$ to nitrate (0.4). $\Delta NOx_{ij}$ represents the reduction in $NO_x$ emissions from TI&TU in that particular county and year, and $NOx_{ij}$ is the total $NO_X$ emissions in the SJV Air Basin in year i and county j, retrieved from the EMFAC database.

[4] The average odometer readings were 194,328 (TSI) and 196,269 (ASM). The average model years are 1995 (TSI) and 1996 (ASM).

$PM_{2.5ij}$ are the baseline nitrate $PM_{2.5}$ values from the SJVAPCD, aggregated into county values[5]. Therefore, $\Delta PM_{2.5\,ij}$ *is* the change in nitrate $PM_{2.5}$ in county *j* during year *i.* We calculated this for all eight counties and all years of the study period.

2.4 Calculating Premature Deaths Avoided

Equation 2 below is a well-established log-linear concentration response function, based on Cox proportional hazards regression analysis, and used in many other health impact studies and benefits analysis tools (Nasari et al., 2016; US EPA, 2017a).

$$\sum \Delta m_{ij} = \sum \left(1 - \frac{1}{\exp\left(\beta * \Delta \mathrm{PM}_{2.5_{ij}}\right)}\right) * I * Pop_{ij} \qquad (2)$$

In equation 2 above, $\beta$[6] represents the health impact caused by each change in unit of $PM_{2.5}$, which is a California-specific rate derived from a recent epidemiologic study (Jerrett et al., 2013). $I$ is the baseline premature death rate from the CDC WONDER data, $Pop_{ij}$ is the total population in each county (adults over the age of 30), and $\Delta PM_{2.5\,ij}$ is the output from formula 1. Therefore, $\Delta m_{ij}$ is the change in mortality in year *i* and county j that can be attributed to the TI&TU program. Mortality was calculated by county and summed to provide estimates cumulatively for the entire SJV.[7]

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[5] We also multiplied the county values by the percent of $PM_{2.5}$ that is nitrate (approximately 40%), to get the baseline nitrate $PM_{2.5}$ values.

[6] Many studies have estimated percent increases in relative risk associated with chronic $PM_{2.5}$ exposure, which translates into a β value (the change in mortality associated with a one unit change in $PM_{2.5}$). We used the Jerrett et al. 2013 study for our concentration response function since it is California-based epidemiological research and therefore relevant for this study (Jerrett et al., 2013; Wang, Jerrett, Sinsheimer, & Zhu, 2016). This value is the best possible option due to the regional specificity, but without a county-specific value the estimates are not entirely precise.

[7] For entries with repair dates listed (Valley CAN did not begin tracking this until 2015) the repair year was used as the year for the purpose of our analysis. For all other entries, the year of the event date was used.

## 3. Results

### 3.1 Tons of $NO_X$ Reduced and Premature Deaths Avoided

Over the course of 2012-2017, the TI&TU program successfully reduced $NO_X$ emissions by approximately 137 tons total, or 274,000 pounds. By the end of 2018, the repairs conducted through 2017 will have resulted in 149 tons reduced[8], or 298,000 pounds. As shown in Table 1, the percent of tons reduced in each county align with the percent of total repairs, indicating that repair efficiency is comparable in each county. They also match fairly well to the percent of the population each county houses in most regions, though the reductions in Tulare and Madera are proportionally much larger than the population percentage.

***Table 1.*** *County Estimates for the Percent of Tons of $NO_X$ Reduced by the Program, Percent of Total Repairs, & Percent of Population*

| County | Tons of NOx Reduced (2012-2018) | Percent of Total Tons of $NO_X$ Reduced | Percent of Total Repairs | Percent of SJV Population |
|---|---|---|---|---|
| Fresno | 28.6 | 19.2% | 19.5% | 23.5% |
| Kern | 21.3 | 14.3% | 16.1% | 21.2% |
| Kings | 8.1 | 5.5% | 5.2% | 3.7% |
| Madera | 12.3 | 8.2% | 7.7% | 3.8% |
| Merced | 10.7 | 7.2% | 7.2% | 6.5% |
| San Joaquin | 22.5 | 15.1% | 16.0% | 17.4% |
| Stanislaus | 20.5 | 13.7% | 14.0% | 12.9% |
| Tulare | 25.3 | 16.9% | 14.3% | 11.1% |
| *Total* | *149* | *100%* | *100%* | *100%* |

*(Source of Population Estimates: US Census Bureau, 2017)*

An estimated .24 premature deaths[9] were avoided from the TI&TU program's repairs conducted from 2012-2017, including the aforementioned benefits in 2018 from previous repairs. This only refers to health benefits from the $NO_X$ emission reductions contributing to particulate

[8] For reference, 149 tons is approximately .4% of annual emissions in the San Joaquin Valley air basin listed in the EMFAC database, as of 2017.

[9] This only accounts for adults ages 30 and up due to the nature of the concentration response function.

matter pollution, and does not account for $NO_X$-specific benefits or benefits related to any other pollutants.

3.2 Sensitivity Analyses

Figure 3 below displays the results of several sensitivity analyses along with our main (point) estimates. These robustness checks illustrate that our point estimates do not vary significantly under different parameters, except when repair deterioration is left unaccounted for.

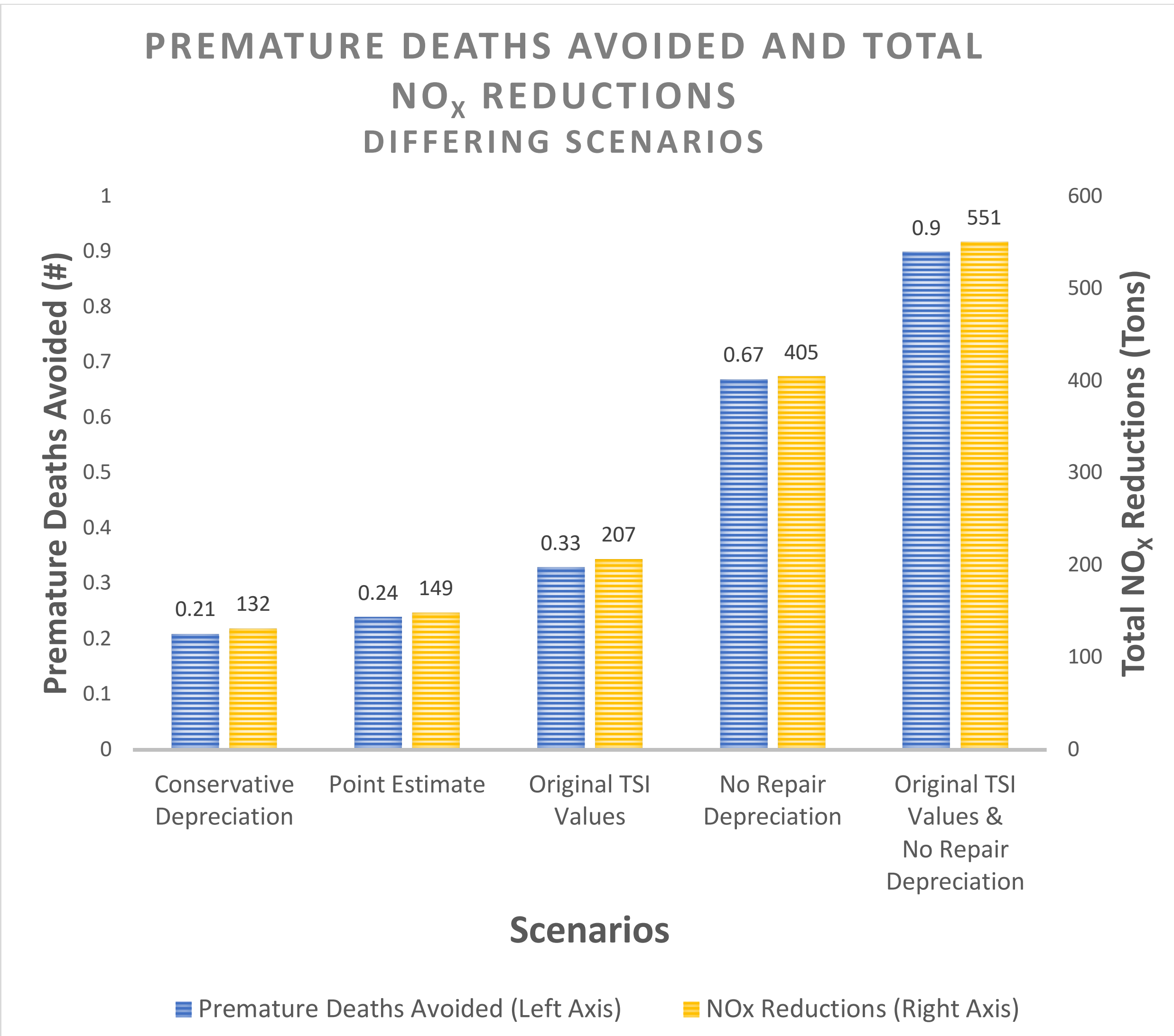


***Figure 3***. *Multiple scenarios of the estimated total $NO_X$ reductions and estimated total premature deaths (adults 30+ years of age) avoided in the SJV from 2012 through 2018 resulting from TI&TU program repairs conducted from mid 2012-2017. The point estimate involves a calculated repair depreciation function.*

*3.2.1 Conservative Depreciation Function*

In a scenario in which a more conservative deterioration function is used for the calculations (essentially, less abatement is expected each year for any given vehicle), approximately 132 tons total would have been reduced from 2012-2018, and .21 premature deaths would have been avoided through the end of 2018.

*3.2.2 Original TSI Values with Repair Depreciation*

In a scenario in which the original TSI values for emission reductions are used for the calculations, and repair deterioration is accounted for, approximately 207 tons total would have been reduced from 2012-2018 from repairs occurring through 2017, and .33 premature deaths would have been avoided through the end of 2018.

*3.2.3 No Repair Depreciation*

In a scenario in which the smog repairs do not deteriorate over time, and the emission reductions continue to accrue annually, 405 tons would have been reduced from 2012-2018. Through the end of 2018, approximately .67 premature deaths would have been avoided from these repairs.

*3.2.4 Original TSI Values with No Repair Depreciation*

Using the original TSI values, and assuming smog repairs do not deteriorate over time and the emission reductions continue to accrue annually, 551 tons of $NO_X$ would have been reduced from 2012-2018, for repairs conducted through 2017. In this scenario, approximately .9 premature deaths would have been avoided from these repairs.

## 4. Discussion

### 4.1 Emission Reductions & Mortality Implications

The sensitivity analyses demonstrate that the mortality impacts do not vary significantly based on the substitution of ASM average reductions for vehicles which received TSI tests. In the scenario of no repair depreciation, the $NO_X$ reduced and premature deaths avoided would double. This scenario is not conceivable, but it is possible that the repairs did not depreciate as quickly as we anticipated for the point estimate, and the actual value may lie somewhere in between the two.

Regarding the quantity of tons reduced, the BAR estimates that through the CAP program repair component for fiscal year 2016-2017, they reduced 62 tons of $NO_X$ for only 4,395 repaired vehicles (California Bureau of Automotive Repair, 2018) as compared to TI&TU's total reduction of 149 tons over the 6 year study period, and 17,000 repaired vehicles. There may be several reasons why the BAR's numbers are slightly different; they may not be incorporating repair deterioration, and it is also not clear how their values are calculated. They may be estimating these values based off of a standard value, not actual pre- and post-repair emission reductions.

The Wang et al. study referenced earlier evaluated the impacts of hidden $NO_X$ emissions due to the highly publicized Volkswagen Group of America (VW) scandal. VW violated EPA standards by producing approximately 11 million vehicles (worldwide) with emission defeat devices. These devices essentially enabled the engines to control emissions under testing conditions, and while on-road the engine treatment does not work efficiently, with the vehicles in some cases emitting 40 times that of the emissions standard (US EPA, 2017d; Wang et al., 2016). The entire VW scandal in California involved approximately 50,000 vehicles, and the research team estimated 12 premature deaths resulting from the hidden emissions from 2009-2016 (Wang et al., 2016). They calculated annual values as well, and the estimate of .24 premature deaths avoided for all years of TI&TU's operation is comparable to the .42 value that Wang et al. found for the first year of the VW scandal, 2009 (Wang et al., 2016). The comparability of these values speaks to the magnitude of TI&TU, considering the scale of the VW incident in California, and the fact that the TI&TU program is only operating in 8 of California's 58 counties (and the SJV only represents approximately 10% of the entire state's population).

As mentioned in Section 1.4, this type of health impact analysis is rarely conducted for similar transportation initiatives, including other vehicle repair programs, or retirement and replacement programs. This is even true for larger programs with multiple goals along with emission reductions, such as the federal "Cash for Clunkers" program intended to stimulate the economy;  several studies evaluated the environmental and economic impacts, but did not touch upon the morbidity or mortality benefits, or lack thereof (Li, Linn, & Spiller, 2013; Mian & Sufi, 2012). However, Health Impact Assessments (HIAs) are conducted regularly, many for proposed transportation projects or policies (Rhodus, Fulk, Autrey, O'Shea, & Roth, 2013). An HIA evaluating fare increases and reduced public transportation service in Boston, MA, used similar methods to ours and found that the proposed changes, including 34-64 million fewer public transit trips annually, would cause between .18 and .26 additional deaths each year due to air pollution, which is comparable to our point estimate of premature deaths avoided from TI&TU repairs (James, Ito, Buonocore, Levy, & Arcaya, 2014). On a larger scale, another study focused on varying land transportation scenarios in London versus Delhi, and found that a scenario with lower carbon emission vehicles (reducing emissions factors) in London would avoid 17 premature deaths from air pollution per 1,000,000 population annually (Woodcock et al., 2009). Lastly, a study on the SJV found that 460 premature deaths would be avoided each year if the entire region reached attainment with federal $PM_{2.5}$ standards (Hall et al., 2006); while this has a much larger scope than TI&TU, it does highlight the substantial impact that environmental exposure has on the population in the region, and emphasizes the necessity of reducing $PM_{2.5}$, which can occur through programs like TI&TU.

Though each of these types of evaluations utilize similar methodologies and provide useful contributions, it is difficult to make relevant comparisons to TI&TU that could actively influence policy and practice. Thus, we hope that our study paves the way for future evaluations to include mortality considerations in the assessment of vehicle emission reduction programs specifically.

4.2 Additional Health Impacts

As mentioned briefly in the introduction, recent research has investigated the sole health impacts of $NO_X$ on mortality. We did not have the capacity to expand our estimation for TI&TU to include isolated $NO_X$ impacts, but this is a burgeoning research area and deserves further study. We may be underestimating mortality impacts from $NO_X$ by assuming that the entirety of mortality impacts are associated with nitrate $PM_{2.5}$.

When considering other potential impacts to public health, it is important to note the complex relationship between $NO_X$, volatile organic compounds (VOCs), and ozone. Ozone is produced by photochemical reactions between $NO_X$ and VOCs and is known to cause respiratory irritation and damage (US EPA, 2017c).The SJV is believed to operate under a $NO_X$ limited regime, meaning that ozone production is more dependent on $NO_X$ concentrations. Thus, agencies have focused regulatory action on reducing $NO_X$ (SJVAPCD, 2013). Therefore, it is likely that the $NO_X$ reductions from TI&TU have reduced ozone-related health impacts as well.

Lastly, there are associated morbidity impacts, which we are unable to expand upon in this study; we will do so in the next stage of our analysis.

4.3 Monetary Analysis

We can relate our mortality estimates to a Value of a Statistical Life (VSL), which is defined as the amount that individuals would pay to reduce their personal risk of dying over the course of a year (US EPA, 2018b). The US EPA currently considers a VSL to be $7.4 million in 2006 dollars[10]; using this estimation, the TI&TU program resulted in $1.85 million in mortality benefits, which is approximately 15% of the program expenditures on these repairs. Accounting for inflation[11], the mortality benefits were $2.18 million, or 17% of program expenditures.

Though this is a small percentage of the full costs, it is important to recognize that the monetized benefits estimated in this paper represent a lower bound, or minimum, of the outcomes of the program. Apart from the social welfare benefits of TI&TU, there are other factors related to pollution to consider. Graff Zivin and Neidell found that ozone exposure reduces agricultural worker productivity, which is a particularly relevant concern in an agriculture-heavy region such as the SJV; the authors highlighted that this is a previously unstudied environmental consideration to be included in decision-making processes (Graff Zivin & Neidell, 2012). Additionally, our estimates do not account for impacts on individuals below the age of 30, though research has found that $PM_{2.5}$ is associated with infant mortality (Son, Lee,

[10] Empirical research indicates that VSL varies at differing ages and therefore could be age-adjusted, though there are discordant findings regarding the nature of this variation (Kniesner Thomas J, Viscusi W. Kip, & Ziliak James P, 2006, Aldy & Viscusi, 2008). Since income is lower in the SJV than the rest of the state (see Section 1.2), this may impact VSL as well.

[11] Calculated using the Bureau of Labor Statistics inflation calculator, using the year 2015 (mid-way through our study period).

Koutrakis, & Bell, 2017; Woodruff, Parker, & Schoendorf, 2006). One research group evaluated the impacts of a $NO_X$ cap and trade program, and found evidence that as pollution decreased, defensive investments (such as medication expenditures) also declined significantly, as did the summertime mortality rate (Deschênes et al., 2017). As mentioned in the previous section, there are also benefits associated with morbidity. A comprehensive cost-benefit analysis, to be conducted in our next stage of research on TI&TU, will incorporate morbidity, social welfare and several of the other aforementioned benefits to develop more robust economic estimates.

As highlighted previously, there are not many studies that are comparable to this in terms of evaluating the impact of a vehicle emission reduction program, particularly at the grassroots level. However, we hope that this study will open the door for future research to utilize environmental health methods to evaluate and monetize the outcomes from comparable transportation programs. This has the potential to have a significant impact on public health and environmental justice, in the SJV and in other regions more broadly.

4.4 Limitations

In Section 4.2 above, we mentioned that our mortality calculations are likely underestimates due to the inability to evaluate the sole impacts from $NO_X$ exposure unrelated to $PM_{2.5}$. Additionally, since our research design only accounts for the impacts of nitrate $PM_{2.5}$ from $NO_X$, and does not incorporate the reduction of other pollutants from vehicle exhaust, our point estimate is likely an underestimate of the true mortality impacts in the SJV resulting from the operation of the TI&TU program. Also, depending on the true nitrate conversion rate and baseline nitrate $PM_{2.5}$ values, our estimates would vary slightly (Wang et al., 2016).

Additionally, in this study, we did not factor in the extent to which travel is occurring outside of the Valley for SJV residents in our analysis framework. If the miles driven are in a different region, the benefits will not have been reaped in the SJV and our calculations may be an overestimate, though not likely by much. We plan to incorporate this into the next stage of our analysis for this project.

The calculations conducted by Valley CAN to produce the annual emission reduction values present some uncertainty, since many of the values included in the calculations were reliant on accurate manual data entry. However, the general formula for converting pre- and post-emission test values to FTP values from the Carl Moyer Program Guidelines is described in a CARB report and has been used in other research (Mérel et al., 2014) as a reliable conversion method, so it is unlikely that this is a major source of error in our study (California Air Resources Board, 2008).

Lastly, it is important to note that this evaluation only accounts for the five and a half most recent years of the TI&TU program, which has been operating since 2005.

## 5. Conclusion

This study estimates the $NO_X$ emission reductions and associated mortality impacts of an environmental justice smog repair program in the San Joaquin Valley: Valley Clean Air Now's Tune In & Tune Up program. We found that from five and a half years of operation of the TI&TU program, and almost 17,000 repairs, approximately .24 premature deaths will have been avoided through the end of 2018 from 149 tons (or 298,000 pounds) of $NO_X$ reductions and the resulting reduction of nitrate $PM_{2.5}$ exposure. Considering the EPA's assigned Value of a Statistical Life, these mortality benefits account for approximately 17% of the TI&TU program's repair expenditures. Though this is a small percentage, this only accounts for a lower bound of the potential benefits of the program, and a robust cost-benefit analysis should incorporate other considerations, such as social welfare and morbidity.

We build upon Pierce & Connolly's findings, which indicated that the TI&TU program achieved distributional equity goals while operating efficiently and producing positive environmental outcomes (Pierce & Connolly, 2018). This is one of the first studies to not only estimate emission reductions from a vehicle repair, retirement, or replacement program, but to also calculate resulting mortality impacts. To our knowledge, this is also the first study to apply findings from Mérel et al. to quantify the depreciation of pollution abatement from smog repairs in California (Mérel et al., 2014). The next stage of this project will involve a cost-effectiveness analysis of TI&TU. The relationships between air quality, transportation policy, health, and environmental justice will remain relevant in California's evolving environmental policy landscape. Until the California vehicle fleet transitions to cleaner technologies or other alternative transportation methods (which still meet the needs of low-income populations in transit-deprived areas such as the SJV), future research on the public health impacts of comparable vehicle emission reduction programs is necessary to inform the effective design of transportation policies and programs.

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