



Estimating mortality impacts from vehicle emission reduction efforts: The Tune In and Tune Up program in the San Joaquin Valley

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ABSTRACT

As a response to profoundly 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 used data on approximately 19,000 repaired TI&TU vehicles from 2012 to 2018, and several estimation techniques, to quantify a range of nitrogen oxides (NO_x) emissions prevented as a result of the program. We then calculated 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 six years of operation of the TI&TU program has reduced NO_x emissions by approximately 53–302 tons by the end of 2018. Using a concentration response function for ambient PM_{2.5}, we found that between 0.055 and 0.31 premature deaths have also been avoided. We present multiple methods for assessing public health impacts, which can be used as guidance for evaluating similar transportation-based emission reduction programs.

1. Introduction

The United States (US) vehicle fleet is significantly cleaner than it was several decades ago (Dallmann and Harley, 2010), and California maintains more stringent emission standards than the US Environmental Protection Agency (EPA) (US EPA, 2018a). Yet, transportation is still the largest source of smog formation in California (California Air Resources Board, 2018a). Vehicle emissions represent a particularly pressing environmental justice issue in the San Joaquin Valley (SJV), a car-dependent region in California containing eight counties, 10% of the state's population, and a higher proportion of minority and low income residents than the state overall (US Census Bureau, 2017). The majority of census tracts in the SJV are California Senate Bill 535 (2012) “disadvantaged community” (DAC) tracts, as determined by the widely-used California Office of Environmental Health Hazard Assessment's (OEHHA) CalEnviroScreen tool (OEHHA 2018). The SJV has two major highways which contribute substantially to local air pollution (Huang and London, 2012; Ngo et al., 2010). In addition to the freeways, there is a higher percentage of commuters using light-duty vehicles in the SJV than in the state overall (US Census Bureau, 2017). As a result of this and several other factors, such as the air

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basin's shape and agricultural activities, air quality in the SJV has historically been poor, and the region remains out of compliance with the National Ambient Air Quality Standards (NAAQS) for ozone and fine particulate matter (PM_{2.5}) (US EPA, 2017a).

To reduce vehicular emissions in the United States, certain regions have Clean Air Act-mandated state specific inspection and maintenance (I/M) programs in place, depending on NAAQS attainment status (US EPA, 2018b). In California, this effort is called the Smog Check Program. Smog checks involve visual and functional inspections, as well as the measurement of vehicle tailpipe emissions [hydrocarbons (HC), carbon monoxide (CO), and typically nitrogen oxides (NO_x)], which are then compared to established thresholds to determine if a vehicle reaches emission standards. If a vehicle does not pass the screening, the owner brings the vehicle to a smog repair station and must pay to repair the emission control system. Currently, this inspection is the only emissions-related regulation in place that vehicle owners are required to comply with after purchase of a vehicle, and thus an incredibly crucial point of pollution prevention. Not all individuals, however, can afford the mandated vehicle repairs resulting from a smog check failure, particularly in low-income regions, such as many areas of the SJV. This is why the Tune In & Tune Up (TI&TU) program, described below, is both timely and imperative.

The SJV's vulnerable population, vehicle dependency, and subsequent high levels of mobile source emissions motivated the nonprofit organization Valley Clean Air Now (Valley CAN) and the San Joaquin Valley Air Pollution Control District (SJVAPCD) to develop and implement the TI&TU smog repair program in 2005. TI&TU is funded by the SJVAPCD through enhanced vehicle registration fees and provides free emissions testing and vouchers for smog repair for SJV residents. Each resident is eligible to receive one voucher per vehicle each year if they fail a smog test, and they can either bring their car to be tested at the TI&TU events or bring a Vehicle Inspection Report from a smog shop that confirms a failed emission test.¹ Since California's smog check program requires the majority of vehicles to pass an emissions test before owners are able to register their vehicles, there is a substantial barrier to registration for owners who are not able to pay for smog repairs. While there are several programs incentivizing vehicle repair, retirement, or replacement in California, each of which offer a financial incentive to households to motivate participation [such as the California Consumer Assistance Program (CAP), the California Clean Vehicle Rebate Project, and the Enhanced Fleet Modernization Program], TI&TU's program design reduces or removes many of the barriers to participation (faced by low-income households), which may also be present in other vehicle emissions reduction programs. Additionally, TI&TU is the first large-scale program in California to implement a grassroots approach to providing underserved households with vehicle assistance (Pierce and Connolly, 2018). Since TI&TU expanded in 2012, it has since served over 50,000 participants. From July 2012 to September 2018 (our analysis period), TI&TU distributed approximately \$12.8 million in smog repair vouchers to SJV residents.

A recent report evaluates the efficacy, distributional equity, and environmental impact of TI&TU, finding that it successfully distributed various benefits to the most disadvantaged areas of the region, and of the state (Pierce and Connolly, 2018). Moreover, it asserts that TI&TU can serve as a model for future transportation programs designed to ameliorate heightened air quality concerns and achieve environmental justice goals, especially in low- to moderate-density regions (Pierce and Connolly, 2018). While this report evaluated several facets of the program, it did not directly quantify the health benefits resulting from the program's repaired vehicles.

Vehicle exhaust primarily contains CO, HC, particulates, and NO_x, the last of which is the focus of our study (Brugge et al., 2007; Westerholm and Egeback, 1994). 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, a phenomenon which is well-established. NO_x can transform into nitrate, which composes approximately 40% of PM_{2.5} in the SJV; levels vary based on region and season (California Air Resources Board, 2016). There is strong evidence indicating that PM_{2.5} pollution adversely impacts cardiovascular and respiratory health through a variety of potential pathways (Anderson et al., 2012; Pope and Dockery, 2006). Previous research has quantified global and local mortality due to PM_{2.5} exposure; a recent study based on the global burden of disease project estimated that ambient PM_{2.5} pollution resulted in approximately 8.9 million deaths globally in 2015, which is significantly higher than previous estimates (Burnett et al., 2018). The impact of poor air quality on human health is well-established, not only globally and in California, but in the SJV region specifically (Meng et al., 2010; Padula et al., 2014, 2013). A 2006 report estimated that if the Valley met PM_{2.5} and ozone standards, the region would save approximately \$1000 per person per year, and avoid 460 premature deaths (Hall et al., 2006). Lastly, a study estimating the environmental impact of the California Smog Check Program found that fixing vehicles more than ten years old, most of the TI&TU vehicle fleet, provided more than 80% of the emission reduction benefits, highlighting the magnitude of this program's potential impact (Singer and Wenzel, 2003). Therefore, this health impact analysis is necessary, and particularly salient for a region such as the SJV with existing environmental and social vulnerability.

The primary objectives of our study were (1) to quantify NO_x emission reductions resulting from TI&TU repairs, and (2) to estimate mortality impacts. Notably, based on an extensive literature search, no other studies of vehicle emission reduction programs have evaluated benefits in terms of mortality. While several other vehicle emission reduction programs within the state and country have been evaluated with regard to environmental and economic efficiency, they have not estimated, and occasionally not even mentioned, public health impacts (Li et al., 2013; Mian and Sufi, 2012). Our study can serve as an assessment model to evaluate the health impacts of a growing number of these programs.

¹ For further information about the operation of TI&TU events, the vehicle fleet and equitable geographic reach of the program, please see Pierce and Connolly (2018).

2. Methodology

2.1. Data sources, extraction, and management

2.1.1. TI&TU vehicle emission reductions

Valley CAN provided our research team with access to a Salesforce database with participant-level information collected at TI&TU events and pre- and post-repair emission measurements sent to Valley CAN from vehicle repair shops. The emission data from the TI&TU program do not include any additional information on the type of repair. Due to the nature of Salesforce's platform, different pieces of data were in different datasets (called "objects" in Salesforce) within the same database; the data were joined together in RStudio using various keys provided to us by Valley CAN's external Salesforce consultant, and were based on a vehicle or participant number, depending on the dataset. The resulting joined data linked each vehicle, including its pre- and post-repair emissions, with all available participant-level data, including the participants' census tract (the tracts were automatically determined within Salesforce based on the participant address). We did manual checks to confirm the reliability of the joins.

All data were cleaned and erroneous data (less than 10%, presumably due to manual entry) were removed, which included incomplete entries, duplicate entries, and all vehicles from outside of the SJV. There were no notable trends regarding which entries had data issues resulting in exclusion. Of approximately 50,000 vehicles which entered the TI&TU program during the time period of July 2012–September 2018, approximately 19,000 vehicles were repaired and had sufficient data to complete emission reduction calculations; these are the vehicles we used for our analysis.

2.1.2. Additional data sources

Data on total NO_x emissions in the SJV during the years of 2012–2018 were extracted from the California Air Resources Board's (CARB) State Implementation Plan Standard Emission Tool database (California Air Resources Board, 2019a). For consistency, we also used CARB's annual $\text{PM}_{2.5}$ values by county for the years of 2012–2018, from their Air Quality Data Statistics website, for our analysis (California Air Resources Board, 2019b). Baseline premature death estimates (2013–2015) for each SJV county were obtained from a Centers for Disease Control and Prevention (CDC) dataset (CDC WONDER), and extracted from the County Health Rankings website (University of Wisconsin Population Health Institute and Robert Wood Johnson Foundation, 2017). Lastly, population estimates were retrieved from the American Community Survey 2015 5-year estimates (US Census Bureau, 2017).

2.2. Calculating annual NO_x emission reductions from pre- and post-repair emissions tests

We used three methods to develop a range for NO_x emission reduction estimates for repaired vehicles. Each method was based on a formula used to convert pre- and post-repair emission measurements from parts per million to grams per mile. This formula accounts for various vehicle characteristics, including odometer reading, vehicle type and model year, and was used to convert our existing emission measurements from Acceleration Simulation Mode (ASM, in parts per million) to Federal Test Procedure (FTP, in grams per mile). Thus, this formula will be referred to as "ASM to FTP" calculations throughout this article. The inputs and coefficients for the NO_x ASM to FTP formula were developed from a regression analysis, with FTP measurements as the outcome variable and ASM measurements and other various vehicle characteristics as the covariates; the regression analysis that was conducted to derive the formulas utilized a dataset which had both ASM and FTP measurements for each vehicle.

The first versions of these ASM to FTP formulas (which were not only developed for NO_x , but for CO and HC as well) were developed in the late 1990s, but have been subsequently updated and published in a 2004 Bureau of Automotive Repair (BAR) and Sierra Research Group technical support document (California Bureau of Automotive Repair and Sierra Research Group, 2004). This report was cited by CARB in the appendices of its 2008 Carl Moyer Program Guidelines (California Air Resources Board, 2008). This early iteration of the formulas from 2004 has been used previously in studies of smog repair efficacy (Mérel et al., 2014), and is what we used for Method 1, described in Section 2.2.1 below.

A more recent version of the formulas provided by BAR and CARB yield substantially different results (Niemeier, 2016), and is what we used for Methods 2 and 3, described in Sections 2.2.2 and 2.2.3 below.²

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 all of our calculations (California Air Resources Board, 2018b). For all three methods described in detail below, we used annual vehicle miles traveled (VMT), calculated based on average odometer reading and model year, to convert from grams per mile to annual emission reductions.

We chose to develop a range instead of a particular point estimate due to uncertainty surrounding these conversions, but we consider the Method 3 estimate described in Section 2.2.3 to be the most accurate (for reasons detailed in Section 4.1). We also present a series of sensitivity analyses in Section 2.6.

² The group that developed the most recent formulas assessed several different regression models in order to optimize the model and reported that the specifications seem robust, but neither the researchers nor any associated agencies claim that the formulas have been fully validated (Niemeier, 2016). The limitations regarding these formulas are discussed in Section 4.5.

2.2.1. Method 1: 2004 conversion calculations³

Prior to the initiation of this study, Valley CAN used the early iteration of the ASM to FTP calculations described in the beginning of [Section 2.2](#) to calculate per-vehicle emission reductions. As mentioned previously, these specific formulas were included in the appendices of the 2008 Carl Moyer Program Guidelines ([California Air Resources Board, 2008](#)) but sourced from a technical support document from 2004, which is why we refer to them as “2004 Conversion Calculations” ([California Bureau of Automotive Repair and Sierra Research Group, 2004](#)). These calculations were adjusted and updated in recent years, and these updated equations were used for Method 2 and Method 3.

2.2.2. Method 2: 2016 conversion calculations

Annual emission reductions for each vehicle were calculated using pre- and post-repair emission measurements as described above, with the most recent version of the ASM to FTP conversion equations provided by BAR. These formulas differ from the earlier iterations in various ways, based on the updated regression outputs; for example, the most recent version includes odometer reading and model year groupings, while the earlier version incorporated vehicle weight and numerical values for model year ([Niemeier, 2016](#)).

2.2.3. Method 3: Emission factors database (preferred estimate)

Using the California Air Resources Board’s (CARB) 2014 Emission Factors (EMFAC) database, which contains data on mobile source emissions and emission rates, we quantified a scenario in which post-repair vehicle emission rates were equal to typical fleet emission rates for the region, as estimated by EMFAC ([California Air Resources Board, 2018b](#)). We calculated a percent change from our estimated pre- to post-repair emission rates quantified in Method 2 and applied that percentage to EMFAC emission rates (the post-repair values, in this scenario) for vehicles of each type and model year in the SJV air basin, to estimate the pre-repair emission rates. This procedure assumes that the *differences* in emission rates pre- and post-repair as calculated by the Method 2 ASM to FTP equations are accurate but acknowledges that the emission rate *values* have inherent uncertainties associated with inputs to the ASM to FTP conversion equations, as mentioned above and in [Section 4.5](#). Using the EMFAC values reduces this uncertainty, and assumes that once the vehicles are repaired, typical fleet emission rates apply to them. Since the EMFAC model is EPA-approved and based on real-world emissions testing, we consider this methodology to be sound.

2.3. Calculating NO_x emission reductions

The emissions abatement return from one-time smog repairs is known to decrease over time ([Mével et al., 2014](#)), so the preliminary emission reductions calculated from each of the three methods are an overestimate, particularly in the years subsequent to repair. To resolve this issue, we applied a depreciation value 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 ([Mével et al., 2014](#)). This study investigated the efficacy of smog repairs as an emissions abatement tool, and they found that 41% of the benefits of abatement (HC, CO, and NO_x) were lost within a two year period post-repair ([Mével et al., 2014](#)). Since we are looking solely at NO_x, and upon recommendation from the first author, Pierre Mével, 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. This is a novel technique for accounting for repair depreciation. More information on the repair depreciation analysis is in [Appendix A](#).

2.4. Converting NO_x emission reductions to PM_{2.5}

The methods for conversion of NO_x to PM_{2.5} described here were adapted from a recently published study evaluating the adverse health impacts of the Volkswagen emission scandal of 2015 ([Wang et al., 2016](#)).

Nitrogen oxides transform into various species after release into the atmosphere. An estimate for the NO_x conversion rate into the secondary nitrates that contribute to PM_{2.5} increases is 0.4 (with a range of 0.3–0.5), which is the value we used in this study ([California Air Resources Board, 2005](#); [Wang et al., 2016](#)). This approximation is particularly appropriate for this study, since it is derived from a study on the SJV specifically ([Kleeman et al., 2005](#)). NO_x annual emission reduction values for each repaired vehicle were converted into PM_{2.5} changes using Eq. (1) below.

$$\Delta PM_{2.5ij} = PM_{2.5ij} * k * \frac{\Delta NO_{xij}}{NO_{xij}} \quad (1)$$

where *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). ΔNO_{xij} represents the reduction in NO_x emissions from TI&TU in that particular county and year, and NO_{xij} is the total NO_x emissions in the SJV Air Basin in year *i* and county *j*, retrieved from the CARB Standard Emission Tool database. $PM_{2.5ij}$ are the baseline nitrate PM_{2.5} values from CARB, aggregated into county values; we multiplied the provided values by the percent of PM_{2.5} that is nitrate (approximately 40%), to get the baseline nitrate PM_{2.5} values. Therefore, $\Delta PM_{2.5ij}$ 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.

³ There are over 1000 fewer repairs within this older version of the data, so final values represent a slight underestimate when compared to the other two methods.

2.5. Calculating premature deaths avoided

To calculate PM_{2.5} related premature death, we used a conventional log-linear concentration response function (Eq. (2)), based on Cox proportional hazards regression analysis reported in many previous health impact studies (Nasari et al., 2016; US EPA, 2017b).

$$\sum \Delta m_{ij} = \sum \left(1 - \frac{1}{\exp(\beta * \Delta PM_{2.5ij})} \right) * I * Pop_{ij} \quad (2)$$

where β 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) which also aligns with findings from a nationwide study (Krewski et al., 2009); 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 $\Delta PM_{2.5ij}$ is the output from formula (1). Therefore, Δm_{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.

2.6. Sensitivity analyses

To contextualize the estimated premature deaths avoided, we conducted four sensitivity analyses. Two of these analyses involved varying assumptions regarding NO_x emission reductions, for Methods 1, 2, and 3: Analysis (a) assumes no repair depreciation and analysis (b) assumes additional repair depreciation, which is a more conservative estimate (the derivation of these depreciation rates is described in more detail in Appendix A). The other two sensitivity analyses represent the bounds of the NO_x to nitrate conversion rate: analysis (c) assumes a conversion rate of 0.5 and analysis (d) assumes a rate of 0.3, which surround the point estimate value of 0.4, as suggested by CARB (California Air Resources Board, 2005). We selected these values to illustrate the entire spectrum of possible impacts.

2.7. Monetary valuation analysis

To provide further context for the premature deaths reduced, we used a simple calculation to estimate the value of the health impacts for each method using 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, 2018c). We used the US EPA's current VSL estimate, which is \$7.4 million in 2006 dollars⁴ (this is approximately \$9.3 million in 2019 dollars). We adjusted for inflation to 2015 dollars, midway through the analysis period (using the Bureau of Labor Statistics inflation calculator), and used that value (approximately \$8.7 million) for our calculations.

3. Results

3.1. Tons of NO_x reduced, premature deaths avoided, and monetary valuation analysis

In general, over the course of 2012–2018, the TI&TU program reduced NO_x emissions by approximately 53–302 tons, or 106,000–604,000 lb, and avoided between 0.055 and 0.31 premature deaths. We separate these estimates by the three methods in the sections below.

3.1.1. Method 1: 2004 conversion calculations

Specifically, in a scenario in which an older version of the ASM to FTP conversion equations are used (Method 1), approximately 152 tons of NO_x would have been reduced from 2012 to 2018, and 0.15 premature deaths avoided, from repairs conducted through 2017. Using the US EPA VSL estimates, this is equivalent to benefits of slightly more than \$1.3 million.

3.1.2. Method 2: 2016 conversion calculations

If the most recent ASM to FTP conversion equations are used (Method 2), approximately 53 tons would be reduced, resulting in 0.055 premature deaths avoided. Monetary benefit analysis using the US EPA VSL value estimates benefits to be approximately \$480,000.

3.1.3. Method 3: Emission factors database (preferred estimate)

Finally, in a scenario in which EMFAC fleet emission rates apply to repaired TI&TU vehicles (Method 3), approximately 302 tons of NO_x would have been reduced from 2012 to 2018, and 0.31 premature deaths avoided. This main estimate of 0.31 for all of the repaired vehicles between 2012 and 2018 is equivalent to approximately 1.6 premature deaths per 100,000 repaired vehicles overall. As previously mentioned, Method 3 is our preferred estimate for reasons described at the beginning of Section 4.1. Using the US EPA VSL value, monetary benefits are equivalent to \$2.7 million.

⁴ 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 et al., 2006). Since income is lower in the SJV than the rest of the state (see Section 1), this may impact VSL as well.

Table 1

Method 3 (EMFAC) Estimates for the Population 30 Years and Older, Total Repairs, Tons of NO_x Emissions Reduced by the Program, Pounds of NO_x Reduced Per Repair, Premature Deaths Avoided, and Premature Deaths Avoided Per 100,000 Repaired Vehicles for each County in the San Joaquin Valley.

County	Number and Percent of SJV Population	Number and Percent of Total Repairs	Tons and Percent of NO _x Reduced	Pounds of NO _x Reduced Per Repair	Number and Percent of Premature Deaths Avoided	Premature Deaths Avoided Per 100,000 Repaired Vehicles
Fresno	498,082 (23.5%)	3,741 (19.9%)	69.8 (23.1%)	37.3	0.070 (22.7%)	1.9
Kern	446,546 (21.2%)	2,993 (15.9%)	41.8 (13.8%)	27.9	0.034 (11.0%)	1.1
Kings	79,032 (3.7%)	998 (5.3%)	15.6 (5.2%)	31.3	0.012 (3.8%)	1.2
Madera	84,270 (3.8%)	1,434 (7.6%)	24.9 (8.3%)	34.7	0.015 (4.9%)	1.0
Merced	133,361 (6.5%)	1,456 (7.7%)	15.8 (5.2%)	21.7	0.010 (3.3%)	0.7
San Joaquin	387,797 (17.4%)	2,959 (15.7%)	39.3 (13.0%)	26.6	0.047 (15.1%)	1.6
Stanislaus	289,817 (12.9%)	2,629 (14.0%)	42.4 (14.1%)	32.3	0.060 (19.4%)	2.3
Tulare	228,860 (11.1%)	2,633 (14.0%)	52.1 (17.3%)	39.6	0.061 (19.8%)	2.3
Total	2,147,765 (100%)	18,843 (100%)	301.7 (100%)	32.0	0.309 (100%)	1.6

Source of Population Estimates: [US Census Bureau \(2017\)](#).

Table 1 only includes findings from Method 3 (EMFAC), our preferred estimate. As shown in the table, the distribution of tons reduced in each county aligns with the distribution of the number of total repairs in some counties, but not all, indicating that repair efficiency varies between counties, with a range of 22–40 lb reduced per repaired vehicle (we used a simple conversion factor for tons to pounds). The least efficient repairs are in Merced County, and the most efficient in Tulare. In Tulare, the vehicle fleet was slightly older than in the other counties (an approximate 1.5 vehicle model year difference from Kern, the county with the newest vehicles and an average model year of 1996), and the vehicles started with the highest emissions at baseline (pre-repair), which likely explains why the percent of reductions is higher than the percent of total repairs.⁵ In Merced County, the pre-repair emission values are the lowest of all the counties, resulting in less of a difference in emission reductions per vehicle. This explains why the efficiency is lower. However, there are no significant differences in the vehicle fleet that explain why Merced vehicles are emitting less at baseline. They do not have the most recent model year or lowest odometer reading average. We do not have sufficient evidence to draw a specific conclusion regarding these discrepancies in repair durability and efficiency, but we believe it deserves further analysis.

The tons reduced also match fairly well to the percent of the population each county houses in several regions, though the reductions in Kings, Madera, and Tulare counties are proportionally much larger than the population percentage. Based on data in **Table 1**, the population and total NO_x reduced, the per capita pounds of NO_x reduced (for individuals aged 30 and above) range from 0.19 in Kern County to 0.59 in Madera County. Repair efficiency considerations aside, these variations are likely partially attributable to the fact that TI&TU events are held as often in the less populated counties as others, despite their smaller population, due to an intentional effort to make the program accessible to all. It is also apparent that the NO_x reductions do not entirely align with the premature deaths avoided (and thus premature deaths avoided per 100,000 repaired vehicles) in each county; this is a function of the total NO_x emission inventory, PM_{2.5} estimates, and population rates used in our calculations. For example, if other sources in the county emit more NO_x overall, the percent change in NO_x from the TI&TU program and resulting PM_{2.5} is smaller, which is the case in Kern County.

For the estimated 0.055–0.31 premature deaths,⁶ the result only refers to health benefits from the NO_x emission reductions contributing to PM_{2.5} and does not account for NO_x-specific benefits or benefits related to any other pollutants, which will be discussed further in [Section 4.2](#).

3.2. Results of sensitivity analyses

Fig. 1 displays the results of the sensitivity analyses (a), (b), (c), and (d), along with our main range estimates, for repairs conducted through 2018. In sensitivity analysis (a), assuming smog repairs do not deteriorate over time and the emission reductions continue to accrue annually, between 139 and 784 tons of NO_x would have been reduced from 2012 to 2018. In this scenario, approximately 0.15–0.87 premature deaths would have been avoided from these repairs. While this is not entirely realistic since repairs will inevitably deteriorate, it provides an upper bound for consideration. In sensitivity analysis (b), where a more conservative deterioration function is used for the calculations (i.e., slightly less abatement is expected each year for any given vehicle), between 43 and 244 total tons would have been reduced from 2012 to 2018, and 0.04–0.24 premature deaths would have been avoided through the end of 2018.

For analysis (c), where the NO_x to nitrate conversion rate is revised from 0.4 to 0.5 and applied to the main estimates, 66–378 tons would have been reduced and 0.07–0.39 premature deaths avoided. For sensitivity analysis (d), where 0.3 is used as the rate, tons reduced are 40–227, and mortality avoided is 0.04–0.23. All of the robustness checks illustrate that our point estimates do not vary significantly under different parameters, except when repair deterioration is left unaccounted for.

All values can be found in [Table C.1](#) in [Appendix C](#).

⁵ For additional details on TI&TU vehicle characteristics, including model year, odometer readings, and emissions test failure rates (for all TI&TU vehicles, not just repaired vehicles), please see [Pierce and Connolly \(2018\)](#).

⁶ This only accounts for adults ages 30 and up due to the nature of the concentration response function.

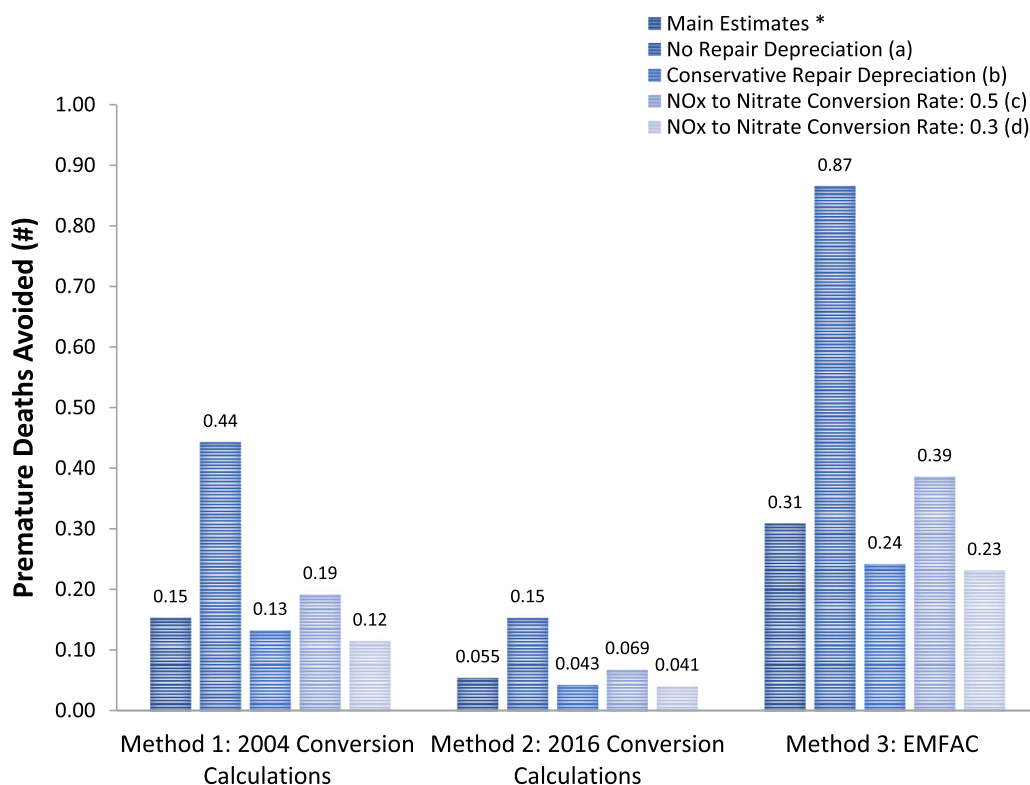


Fig. 1. Multiple scenarios of the estimated total premature deaths (adults 30+ years of age) avoided in the SJV from 2012 through 2018 resulting from TI&TU program repairs, for all three methods. The alternative scenarios are as follows: (a) no repair depreciation, (b) more conservative repair depreciation, (c) NO_x to nitrate conversion rate of 0.5, and (d) NO_x to nitrate conversion rate of 0.3, as seen in the legend. *The main estimates and estimates with varying repair depreciation rates use the CARB-suggested NO_x to nitrate conversion rate of 0.4, as described in [Section 2.6 \(California Air Resources Board, 2005\)](#).

4. Discussion

4.1. Emission reductions & mortality implications

As mentioned previously, EMFAC is EPA-approved, and based on real-world emissions testing. The estimated emission reductions from the EMFAC methodology are higher than the other two methods, which may be because EMFAC represents emissions over the driving cycle rather than at two points of engine load. Previous reports have shown that on-road emissions have been higher than ASM measurements in several cases ([Wenzel et al., 2000](#)). Thus, this method may be more representative of realistic driving conditions, which is why it is our preferred estimate.

The sensitivity analyses demonstrate the importance of accounting for repair depreciation. In the scenario of no repair depreciation, the NO_x reduced, and premature deaths avoided from the reductions in secondary nitrate PM_{2.5} (see the Introduction and [Section 2.4](#) in the Methodology for details) would almost triple. While this scenario is not plausible, it is possible that the repairs did not depreciate as quickly as we anticipated for the main values within the range. These methodological challenges also served to illuminate the need for further research into the rate of emission repair depreciation, which would build on Mérel et al.'s work and improve the precision of future analyses ([Mérel et al., 2014](#)).

We also compare the quantity of tons reduced against the previously mentioned CAP program (run by BAR), which offers repair assistance or vehicle retirement, and has an income threshold for a certain level of participation. Through the CAP repair component for fiscal year 2016–2017, the program is estimated to have reduced 62 tons of NO_x for 4395 repaired vehicles, or 28 lb per vehicle ([California Bureau of Automotive Repair, 2018](#)). These values are comparable to the higher end of our estimated TI&TU values, 53–302 tons of NO_x reductions from 19,000 repaired vehicles over six years (5.6–32 lb per vehicle).

How do the estimates of premature mortality compare to those derived in similar studies? The Wang et al. study evaluated the impacts of hidden NO_x emissions due to the highly publicized Volkswagen Group of America (VW) scandal ([Wang et al., 2016](#)). The VW scandal involved the production of emission defeat devices (which control emissions under testing conditions) and affected approximately 50,000 vehicles in California. Wang et al. estimated 12 premature deaths resulting from the hidden emissions from 2009 to 2015 ([Wang et al., 2016](#)). Additionally, the estimate of 0.055–0.31 premature deaths avoided for all years of TI&TU's operation is of the same order of magnitude of the value (0.42) that Wang et al. found for the first year of the VW scandal, 2009, as well as comparable to our estimate of 1.6 premature deaths avoided per 100,000 repaired vehicles ([Wang et al., 2016](#)). Though the

scenarios are unrelated, the comparability of the magnitude of these values speaks to the scope and impact of the TI&TU program.

As mentioned in [Section 1](#), this type of health impact analysis is rarely conducted for similar transportation initiatives, such as other vehicle repair programs, or retirement and replacement programs. Some studies project potential health benefits from hypothetical interventions to reduce emissions. Other intervention evaluations often include an estimation of emission reductions, but do not take the next step to quantify health impacts. For instance, Health Impact Assessments (HIAs) are conducted regularly, particularly for proposed transportation projects or policies ([Rhodus et al., 2013](#); [Malmqvist et al., 2018](#)). 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 0.18 and 0.26 additional deaths each year due to air pollution, which is comparable to our point estimate of premature deaths avoided from TI&TU repairs ([James et al., 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 emission 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 hypothetical intervention 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. For actual programs that are operating, however, even for larger programs with multiple goals including emission reductions, public health outcomes are usually not measured. For instance, the federal “Cash for Clunkers” program was evaluated in several studies for its environmental and economic impacts, but did not touch upon the morbidity or mortality benefits, or lack thereof, resulting from program deployment ([Li et al., 2013](#); [Mian and Sufi, 2012](#)).

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. Additionally, although HIAs for proposed scenarios are unequivocally informative, this type of analysis is hypothetical. Evaluating existing programs and policies can provide stakeholders with tangible, comprehensive information that can influence decision-making. Thus, we hope that our study paves the way for future evaluations to include mortality considerations in the assessment of similar environmentally-focused transportation programs and policies, in California and more broadly as well.

4.2. Additional health impacts & considerations

Our study investigates the impacts of $PM_{2.5}$ on mortality, which are the most well-researched health impacts within the literature. There are also morbidity impacts associated with reduced exposure to $PM_{2.5}$, such as fewer cases of asthma, other respiratory illnesses, and cardiovascular disease, which we do not address in this study. 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 et al., 2017](#); [Woodruff et al., 2006](#)). Our estimates also do not incorporate the reduction of other pollutants from vehicle exhaust. Therefore, our estimates of health impacts can be considered conservative.

As mentioned briefly in the introduction ([Section 1](#)), recent research has investigated the sole health impacts of NO_x on mortality. California-based research indicates that NO_2 , a component of NO_x , is associated with premature death ([Jerrett et al., 2013](#)). A recent study found a 10% decrease in NO_x reduces mortality by 0.04% ([Deschênes et al., 2017](#)). Related mortality varies regionally, but a study focused on California found that the single pollutant mortality risk for the interquartile range of exposure to NO_2 (4.12 parts per billion) is 1.031 ([Jerrett et al., 2013](#)). Evidence is still emerging regarding the adverse health impacts of NO_x and NO_2 , but the current literature does not allow us to confidently expand our estimation for TI&TU to include isolated NO_x impacts, which requires further study. We may be underestimating mortality impacts from the TI&TU program by assuming that the entirety of mortality impacts are associated with nitrate $PM_{2.5}$. With that being said, some literature (though inconclusive) suggests that nitrate and other secondary particles may be slightly less toxic compared to other PM constituents, which could lead to an overestimation ([Kelly and Fussell, 2012](#)). Also, depending on the nitrate conversion rate and baseline nitrate $PM_{2.5}$ values, our estimates would vary slightly.

When considering other potential impacts to public health, it is also 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 ([Jerrett et al., 2013](#); [To et al., 2013](#)). 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.

One additional consideration is how these health benefits could scale up if this initiative was expanded. If applied outside of the SJV, the extent of the benefits would largely depend on the region the program is expanded to, and thus would not be linear. For our analysis we used region-specific ambient pollution levels, and a California-specific NO_x to nitrate conversion level. It is important to note that this type of program is particularly well-designed for the SJV region, and there are several regional characteristics that make TI&TU work equitably and efficiently, including the vulnerable population, historically poor air quality, insufficient density to successfully build out public transit, the old and high-polluting vehicle fleet, and long commute times for residents. We believe that this type of program will be most successful in regions that fit many of these characteristics. While it is challenging to estimate specifically how the benefits would scale up, it is important to note that there are many regions throughout the United States that might benefit from a similar program until they are able to turn over the vehicle fleet entirely to zero-emission vehicles.

Though we expect the scaled benefits from this type of program (if expanded to other areas in the United States) to be highly dependent on regional characteristics and likely non-linear, we would expect the benefits to linearly increase within the SJV region itself. Even though our analysis only captures data on repairs through late 2018, the estimated benefits will continue over time as the

TI&TU program continues to incentivize repairs. In fact, there have been more than 3500 additional repairs through TI&TU since this analysis was completed.

4.3. Monetary valuation analysis

Using the VSL estimation, the TI&TU program resulted in up to \$2.7 million in mortality benefits in 2015 dollars, or 21% of the program's direct expenditures on vehicle repairs. This is based on Method 3 (EMFAC), our preferred estimate.

Though this is only a percentage of the full costs, it is important to recognize that the monetized benefits estimated in this paper represent a minimum of the beneficial outcomes of the program. Apart from the considerable social welfare benefits of TI&TU (Pierce and Connolly, 2018) and reliable car access more generally (King, et al., 2019), 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 and Neidell, 2012). 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 (Deschênes et al., 2017).

As highlighted previously, there are not many studies which similarly evaluate the health impacts of a vehicle emission reduction program, particularly one targeted at low-income populations. Thus, 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 emission reduction programs.

4.4. Environmental justice implications

The TI&TU program model has been shown to promote equity. Not only does it broadly serve the SJV, one of the most disadvantaged regions within the state, but it has also successfully targeted benefits to the most disadvantaged areas within the SJV as per OEHHA's CalEnviroScreen tool (Pierce and Connolly, 2018; OEHHA 2018). In fact, our analysis indicates that 70% of repairs took place in DAC census tracts. Further, research suggests that personal vehicles are necessary infrastructure to provide low-income populations with access to employment and other opportunities, and indicates that a lack of vehicle access has increased the magnitude of such disparities (King et al., 2019; Blumenberg and Pierce 2014). Putting aside the mortality and morbidity impacts from TI & TU, the program is improving air quality in the areas most impacted and providing social welfare benefits to households most in need by facilitating continued vehicle ownership.

4.5. Other limitations

Besides the limitations related to measuring health impacts discussed in Section 4.2, the calculations we completed to produce the annual emission reduction values also present some uncertainty, primarily because the conversion equations for ASM to FTP have several associated challenges, including data paucity issues surrounding the derivation of the equations, as well as technical limitations in simulating FTP measurements.⁷ The latter account for both hot and cold start vehicle emissions, over a range of transient driving conditions, whereas ASM tests only account for hot start emissions under two engine loads. Unfortunately, no agency or research group has been able to develop universally accepted conversion equations, though several iterations of these calculations have been produced since the late 1990s. We corresponded with both BAR and CARB regarding these issues, and despite the uncertainty, we have determined that using these equations is useful in deriving our estimate range, particularly since a previous version of these equations was used as a reliable conversion method (Mével et al., 2014).

Additionally, the repair depreciation function we used in this study is based on findings from one research study, and it is not guaranteed that all vehicles will follow the same emissions trajectory. However, the authors did find their multiple model specifications to be robust, and they used a California vehicle fleet in their analysis, like we did in this study as well (Mével et al., 2014).

Though not a limitation of our study, it is also important to note that programs such as California's Smog Check Program utilize significant funds, and while some studies have previously estimated benefits of the overall program (Singer and Wenzel, 2003), considerable uncertainty remains. Scholars have posed questions regarding the utility and cost-effectiveness of smog repair as a method of emissions mitigation and proposed alternative strategies for increasing efficiency (Ando et al., 2000; Mével et al., 2014). In fact, research indicates that emissions increase at a more rapid rate post-repair than they would have if the vehicle was not repaired, illustrating that there is no way to eliminate the effects of time and use on the emissions of motor vehicles. Of course, there have also been situations where emissions testing does not accurately reflect on-road emissions, like in the previously mentioned VW scandal. We do not argue that smog testing and repair is the most ideal or cost-effective solution to reducing vehicle emissions, rather that until the vehicle fleet can be replaced with entirely clean vehicles, the TI&TU program model is one of the only policies which provides financial and environmental benefits to residents in a region in much need of access to environmental amenities such as clean air.

Generally, the development of a more robust methodology for these types of vehicle emission reduction evaluations, including the types of conversion equations to use, would be extremely useful and resolve many of the existing limitations.

⁷ Additionally, due to methodological uncertainty, we were unable to calculate the FTP values for the 7% of vehicles that were two-speed idle (TSI) tested, so we substituted the average reduction value for acceleration simulation mode (ASM) tested vehicles (please see Appendix B for additional information).

5. Conclusions

We estimated 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 TI&TU program. We found that from six years of operation of the program and almost 19,000 vehicle repairs, 0.055–0.31 premature deaths have been avoided from NO_x emission reductions of 53–302 tons. We conducted four sensitivity analyses, which estimated reductions based on varying repair depreciation and NO_x to nitrate conversion rates; the range of results for all four sensitivity analyses (and all three methods) was 40–784 tons, and 0.041–0.87 premature deaths.

This study is one of the first studies to fully connect the often-siloed topics of air quality, transportation policy, health outcomes, and environmental justice, and makes several contributions to the literature. Until the state vehicle fleet transitions to cleaner technologies or other alternative transportation methods which can 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 policies and programs to reduce emissions from the transportation sector.

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Declaration of Competing Interest

The authors declared that there is no conflict of interest.

Appendix A. Calculating NO_x emission reductions: Detailed methodology for abatement depreciation from smog repair

We developed our depreciation function after consulting with two of the authors of the Mérel et al. study cited throughout our manuscript. This study was California based, and thus an appropriate model to base our calculations on. As mentioned in the main text, we used results from an appropriate alternate model which found that approximately 51% of the abatement for NO_x had diminished two years post-repair. We applied a piece-wise constant function, with the assumption that abatement decreases in a linear fashion each six months, and two years after repair, 51% of the abatement has diminished. Several years post-repair, the repair benefits are gone entirely. This allows for the possibility that deterioration may not be an entirely constant process, but also a severe deterioration event may not occur immediately post-repair. For the conservative repair depreciation estimates in the sensitivity analysis, the assumption that 51% of the abatement for NO_x has diminished two years post-repair still holds, but the vehicle depreciates every year instead of every six months, with a more extreme decrease, starting immediately post-repair.

Appendix B. TSI versus ASM tests

The ASM method is a tailpipe test which measures HC, CO, and NO_x for vehicles on a dynamometer under two engine loads. The TSI method measures HC and CO tailpipe emissions when the vehicle is idling.

For Method 2 (2016 Conversion Calculations) and Method 3 (EMFAC), NO_x reduction values for the small percentage (7%) of vehicles which received a two-speed idle (TSI) test instead of an acceleration simulation mode (ASM) test (these tests differ in the pollutants measured) were not able to be calculated, since NO_x is not measured during TSI tests.

For Method 1 (2004 Conversion Calculations), Valley CAN did calculate emission reductions from TSI tests (6% of vehicles) using a different formula, which 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 groups (the average odometer readings for the full dataset were 192,853-ASM and 195,040-TSI, and the average model years are 1995-ASM and 1996-TSI) indicating the vehicle fleets are comparable, we have no reason to believe the reductions should be this dramatically different. Due to this relative unreliability, the values for the 6–7% of vehicles that were TSI-tested were replaced with the average reduction value for ASM-tested vehicles, for all three methods.

Appendix C. All results

See [Table C.1](#), which includes all findings from the main and sensitivity analyses for all three methods, described within the main text.

Table C.1
Methods 1, 2, and 3 Main Estimates and Sensitivity Analysis Estimates for Tons of NO_x Reduced and Premature Deaths Avoided from the Program.

	Method 1: 2004 Conversion Calculations		Method 2: 2016 Conversion Calculations		Method 3: EMFAC	
	Tons Reduced	Premature Deaths Avoided	Tons Reduced	Premature Deaths Avoided	Tons Reduced	Premature Deaths Avoided
Main Estimates*	152	0.15	53	0.055	302	0.31
No Repair Depreciation (a)	405	0.44	139	0.15	784	0.87
Conservative Repair Depreciation (b)	132	0.13	43	0.043	244	0.24
NO _x to Nitrate Conversion Rate: 0.5 (c)	190	0.19	66	0.069	378	0.39
NO _x to Nitrate Conversion Rate: 0.3 (d)	114	0.12	40	0.041	227	0.23

* The main estimates and estimates with varying repair depreciation rates use the CARB-suggested NO_x to nitrate conversion rate of 0.4, as described in [Section 2.6 \(California Air Resources Board, 2005\)](#).

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