UW Inventory of Freight Emissions (WIFE3) Heavy Duty Diesel Vehicle Web Calculator Methodology

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16. Abstract This document serves as an overview and technical documentation for the University of Wisconsin Inventory of Freight Emissions (WIFE3) calculator. The WIFE3 web calculator rapidly estimates future heavy duty diesel vehicle (HDDV) roadway emissions for the lower 48 U.S. states. Truck emissions are estimated using two primary data sources: a set of regional speed-dependent emission factors and an inventory of road-way specific truck travel. Emission factors are from the U.S. EPA's Motor Vehicle Emission Simulator (MOVES).		
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Table of Contents

1. Background

This document serves as an overview and technical documentation for the University of Wisconsin Inventory of Freight Emissions (WIFE3) calculator. WIFE3 is a third generation emission inventory for diesel-powered long haul freight vehicle emissions. Previous versions are based on work by Bickford et. al.[1], Luedke[2], and Meier et. al.[3]

The WIFE3 web calculator rapidly estimates future heavy duty diesel vehicle (HDDV) roadway emissions for the lower 48 U.S. states. Truck emissions are estimated using two primary data sources: a set of regional speed-dependent emission factors and an inventory of road-way specific truck travel. Emission factors are from the U.S. EPA's Motor Vehicle Emission Simulator (MOVES).[4] MOVES is a powerful tool that allows for a very detailed analysis of vehicle emissions and accounts for a large number of parameters (e.g., meteorology, speed, roadway type). Truck transportation, in terms of vehicle miles traveled (VMT), was based on a roadway-by-roadway inventory of heavy-duty diesel vehicles from the Federal Highway Administration's Freight Analysis Framework Version 3 (FAF).[5]

The MOVES and FAF tools generate large datasets of emissions factor and roadways. This calculation is simplified by assigning regional emission factors based on a representative location, and condensing vehicle travel data into characteristic distributions. The resulting emission calculation is a trivial multiplication across a large array of vehicle travel for each road-segment by an emission factor specific to location, roadway, and speed.

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[1] Bickford E, Holloway T, Karambelas A, Johnston M, Adams T, Janssen M, Moberg C. 2013 *Emissions and Air Quality Impacts of Truck-to-Rail Freight Modal Shifts in the Midwestern* U.S. Environ. Sci. Technol., DOI: 10.1021/es4016102

[2] Luedke M.C. (2011). Evaluation of eastern U.S. air quality scenarios for trucks, electricity, and natural gas (Master's Thesis, University of Wisconsin-Madison).

[3] Meier PJ, Holloway T, Luedke M, Frost E, Scotty E, Williams S, Bickford E. (2013) *Does Natural Gas Make Sense for Freight? Environmental Implications of the "Pickens Plan"*. National Center for Freight & Infrastructure Research & Education (CFIRE 04-22).

[4] U.S. EPA (2012) Motor Vehicle Emission Simulator. Available: http://www.epa.gov/oms/models/moves/.

[5] U.S. Department of Transportation Federal Highway Administration (n.d.) *Freight Analysis Framework – FAF3 Origin-Destination Data* Retrieved July 30, 2012, from: http://www.ops.fhwa.dot.gov/freight/freight_analysis/faf/.

2. Calculator Overview

The WIFE3 calculator forecasts state-level HDDV highway freight transport for the energy and emissions metrics listed in Table 1.

Table 1. Reported Energy and Emission Metrics

VMT	Vehicle Miles Traveled
Diesel (gal)	Fuel Consumption
MPG	Miles per Gallon Diesel
NOx	Nitrogen Oxides (tons)
SO_2	Sulfur Dioxide (tons)
CO_2	Carbon Dioxide (tons)
CH_4	Methane (tons)
VOC	Volatile Organic Compounds (tons)
CO	Carbon Monoxide (tons)
PM10	Primary Exhaust PM10 - Total (tons)
PM2.5	Primary Exhaust PM2.5 – Total (tons)

To generate a forecast, select the "Query" button. Select one or more states from the drop down menu along with the date range of interest. Select the "Run" button. If this query has been calculated previously, results should be returned instantly. Otherwise, run time may require several minutes. Results are presented in table format as shown in Figure 1. Each metric may be viewed as a time-series chart by selecting the "graph" button above the corresponding column header.

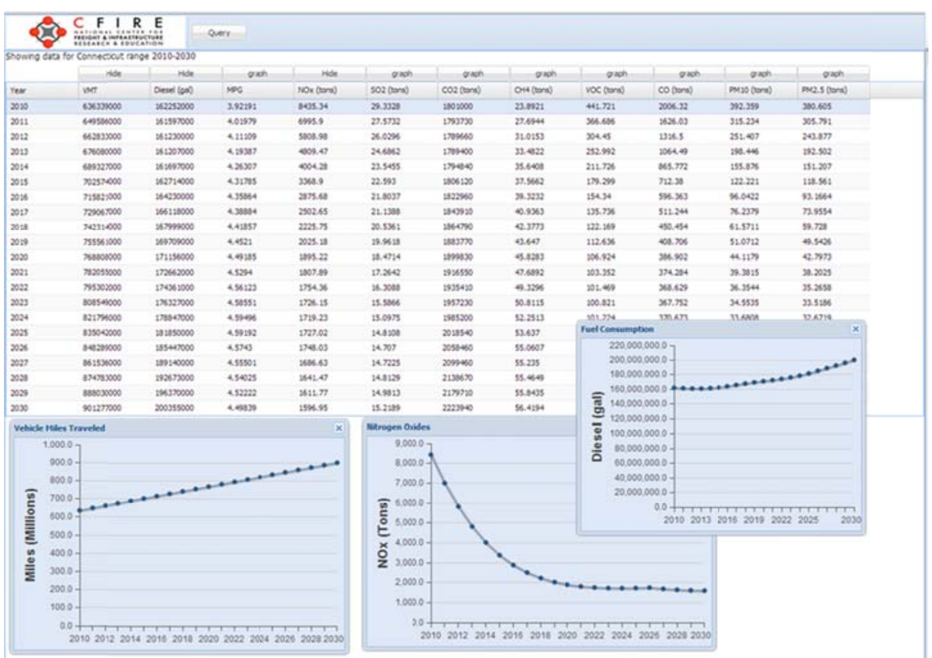

Figure 1. WIFE3 User Interface

The remainder of this document details the user controls, assumptions, and methodology underlying the WIFE3 calculator.

3. Regional Emission Factors

Certain vehicle emissions are heavily dependent on weather conditions. To create state-specific emission factors, we used MOVES for nine U.S. locations, each within one of the nine regions defined by the National Climatic Data Center and regularly used in climate summaries. Figure 2 illustrates the location from which each state's emission factors were generated. For each location, MOVES generated emission factors for each month of the year.

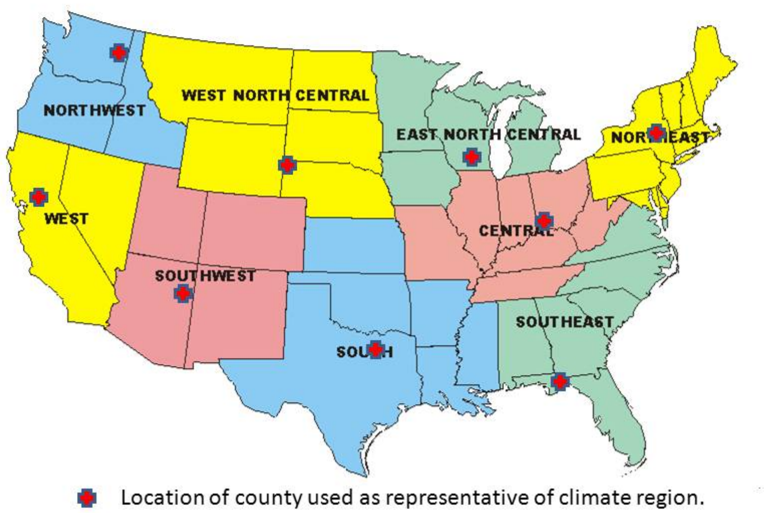

Figure 2 – Nine NOAA Climate Regions[6] and Locations of Counties Used to Generate Regional Emission Factors.

The MOVES generated emission factors are reported in grams pollutant per mile and are unique for every combination of vehicle age, month, road type, speed and year. Each run contains 31 distinct model year vehicles. Emission factors were generated for sulfur dioxide, nitrogen oxides, carbon monoxide, methane, carbon dioxide, and particulate matter. Carbon dioxide emissions are also used to estimate fuel consumption using a conversion factor of 22.2 lb. /gal fuel.[7]

[6] http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/regional_monitoring/regions.shtml
[7] U.S. Environmental Protection Agency, "Emission Facts: Average Carbon Dioxide Emissions Resulting from Gasoline and Diesel Fuel," February 2009.

MOVES model runs were used to generate emission factors for three different years: 2010, 2030, and 2050. MOVES estimates emissions across a vehicle fleet comprised of vehicle models from the previous 31 years, while accounting for deterioration of vehicle performance over time. (MOVES also diminishes the contribution of older model vehicles over time, discussed later.) For years other than 2010, 2030, or 2050, the web calculator interpolates to account for emission factor degradation. For example, the model holds two MOVES generated emission factors for a 2025 vehicle: for 2030 (when vehicle is 5 years old) and for 2050 (when vehicle is 25 years). To estimate the vehicle's 2040 emission rate, the WIFE3 calculator will interpolate between MOVES emission factors (EF) as follows:

(1) $$EF_{2040} = EF_{2030} + (2040 - 2030)[(EF_{2030} - EF_{2050})/(2050-2030)]$$

Depending on the simulated year, and the vehicle model year, two emission factors may be available for interpolation or extrapolation. For model years between 2000 and 2010, we use linear interpolation between the 2010 and 2030 MOVES run data For years between 2020 and 2030, we use linear interpolation between the 2030 and 2050 MOVES run data when the year of interest is less than or equal to 2030. If the year of interest is greater than 2030, the 2050 MOVES run data can be used for all model years from 2020 to 2050.

For model years 1980-1999, 2011-2019, and 2031-2050, only one MOVES generated emission rate is available. For these model years, we analyze how the emission rates change between emission factors with two data points (e.g., 2010 and 2030). We then averaged over all parameters and model years to come up with a pollutant and region specific average emission decay rate (EDR) which represents how a vehicle's emission rates for each pollutant change over time. We assume this behavior is linear. We then apply this decay rate to model years 1980-1999, 2011-2019, and 2031-2050 using a point-slope type formula, where the slope is given by the emission decay rate.

4. Vehicle and Roadway Distributions

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Distribution of Truck Transport by Roadway Link

The Freight Analysis Framework (FAF) integrates data from a variety of sources to create a comprehensive picture of freight movement among states and major metropolitan areas by all modes of transportation.[8] The FAF data provides information for individual road segments, including segment length, road type, average travel speed, and vehicle flux (number of vehicles passing over the road segment per day) for 2007 and forecast for 2040. Speed and vehicle flux are estimated for 2007 and 2040 values. For speeds and flux between (or after) these years, we interpolate (or extrapolate) between these values as necessary using the standard y=mx+b linear equation. We characterize each state's VMT and speed by creating distributions of total VMT and speed by road type (RT), as follows:

Distribution of Truck Transport VMT by Road Type

(2) $\%RoadType = \sum_{RT=a} (length*flux*time) / \sum_{RT=2,5} (length*flux*time)$

Where RT denotes a specific road type (urban/rural, restricted/unrestricted), which in MOVES is identified by a number between 2 and 5 (inclusive). The denominator is summed over all road types.

Distribution of Truck Transport Speed by Road Type

(3) $\%Speed_{RT} = \sum_{S=a} (length*flux*time) / \sum_{S=1,16} (length*flux*time)$

Where S denotes a specific speed bin, which in MOVES is identified by a number between 1 and 16 (inclusive). The denominator is summed over all speed bins for a given road type.

Distribution of VMT by Month

MOVES contains several tables in its standard database which are distributions.[9] To distribute VMT by month, we used the MOVES distribution named movesdb20121030.monthvmtfraction.

Distribution of VMT by Vehicle Age

The vehicle population distribution provides the composition of the vehicle fleet in terms of model year (e.g. vehicle age). The data used to calculate the vehicle population

[8] http://www.ops.fhwa.dot.gov/freight/freight_analysis/faf/

[9] U.S. Environmental Protection Agency (2009) MOVES Software Design and Reference Manual p. 244-245. http://www.epa.gov/otaq/models/moves/420b09007.pdf

fraction comes from the MOVES 2010 Default Age Distributions spreadsheet.[10] We manipulated this spreadsheet to obtain the fraction of total vehicle population by age for each year 1999 to 2050. We did this by dividing the population of a vehicle type for a given age and year by the total population for that vehicle type and year.

The basis for our methodology comes from the NHTSA Vehicle Survivability and Travel Mileage Schedules Report.[11] In this report, the survivability of light duty vehicles is given of the form:

(4) S_{age}=1-exp(-exp(a + b*age))

We adopted this model for use with Combination Unit Long Haul Trucks. Using information from Alabama for years 1999 through 2010, we found the number of tractor-trailer registrations in the state for each year. By using the MOVES default age distribution, we estimated the number of model year 1999-2010 vehicles (ages 0-11) that were included in the registration figures for each year.

For a given model year, we can see what effect age has by taking the ratio of the number of registered vehicles of that year that are X years old to the number of registered vehicles of that year when they were 0 years old. For example, in 2005, model year 1999 cars are 5 years old. Taking the number of model year 1999 cars in 2005 and dividing it by the number of model year 1999 cars in 1999 tells us what fraction of 1999 model year cars are still on the road in 2005. By averaging across all of the years, we obtained a distribution that shows the probability that a vehicle of a given age is still on the road.[12] This resultant distribution was plotted and fitted to a curve to obtain the parameters a and b for Equation 4.

The NHTSA report goes on to give a model of vehicle VMT as a function of vehicle age for light duty vehicles. These functions are of the form:

(5) VMT_{age}=a*age^3 + b*age^2 + c*age + d

To obtain the parameters a, b, c and d, we created a MOVES run to model Combination Unit Long Haul Truck VMT per capita (by dividing total VMT by truck population) for Dane County 2010 as a function of truck age and fitted the data to a cubic function. This yields an average VMT per vehicle as a function of age.

We used these two functions to create a weighted VMT defined by:

(6) $WVMT_{age}$= VMT_{age}*S_{age}

[10] http://www.epa.gov/oms/models/moves/tools.htm

[11] National Highway Traffic Safety Administration (2006) Vehicle Survivability and Travel Mileage Schedules (DOT HS 809 952) http://www-nrd.nhtsa.dot.gov/Pubs/809952.pdf.

[12] We used truck registration data from Alabama in our calculations, and assumed this is representative of the U.S. average.

This function calculates the average VMT per vehicle accounting for vehicle scrappage. That is to say, the VMT per vehicle tells one the average miles a vehicle still on the road would drive, and the weighted VMT (WVMT) tells one the average miles a vehicle of that age group (whether or not it is still on the road) would drive.

By summing the VMT per vehicle from $0 \le age \le 30$ and making the same summation for the weighted VMT, and taking their quotient, we arrive at the average VMT for that vehicle type.

(7) $$AVMT=\sum VMT_{age}/\sum WVMT_{age}$$

The final step is to calculate %VMT(age)

(8) $$\%VMT_{age}=WVMT_{age}/AVMT_{age}$$

We refer to this as the Decay Factor. It tells one, in all likelihood, what fraction of the average VMT (AVMT) a vehicle of that age will be driving, taking into account vehicle scrappage.

5. Quality Assurance

A detailed description of the underlying data used to characterize truck transport is available in the Freight Analysis Framework 3 User Guide.[13] Similarly MOVES guidance is available from the MOVES Software Design and Reference Manual.[14] MOVES does not account for topological or geographic details, nor does it distinguish between any particular designs of vehicle and does not account for emission-mitigation measures except for those built into MOVES. Because our emission factors are weighted averages of the MOVES hourly emission factors with separate emission factors for weekdays and weekends and because our model does not have hourly resolution, time-of-day factors are completely ignored. We also chose to ignore the hourly climatic data generated by the MOVES runs in favor of picking a representative county from each of the nine climatic regions as identified by NOAA. Thus we are assuming that a whole climatic region can be characterized by a single county, and we are ignoring seasonal time-of-day factors such as extreme cold in winter mornings or extreme heat in summer afternoons.

To check whether WIFE3 estimates are reasonable, we compared the web calculator's state-level emission estimates, to emissions reported in the National Emissions Inventory (NEI) for 2008. As vehicle emissions are not directly measured, the NEI values are also estimates. Therefore, it is inappropriate to deem discrepancy as "errors", but it provides a reality check against other reported estimates. As shown in Figures 3 - 7, emission estimates from both sources are generally in the same range, with the exception of PM emissions which are consistently higher than NEI estimates. Some discrepancies are consistent across pollutants. For example, WIFE3 emissions are consistently higher than NEI estimates for Texas and consistently lower than NEI estimates for California. The appropriateness of this inventory for use in Texas, California, or other states with consistent discrepancies should be based on comparison to other local emission estimates.

[13] http://ops.fhwa.dot.gov/freight/freight_analysis/faf/faf3/userguide/#s12

[14] U.S. Environmental Protection Agency (2009) MOVES Software Design and Reference Manual http://www.epa.gov/otaq/models/moves/420b09007.pdf

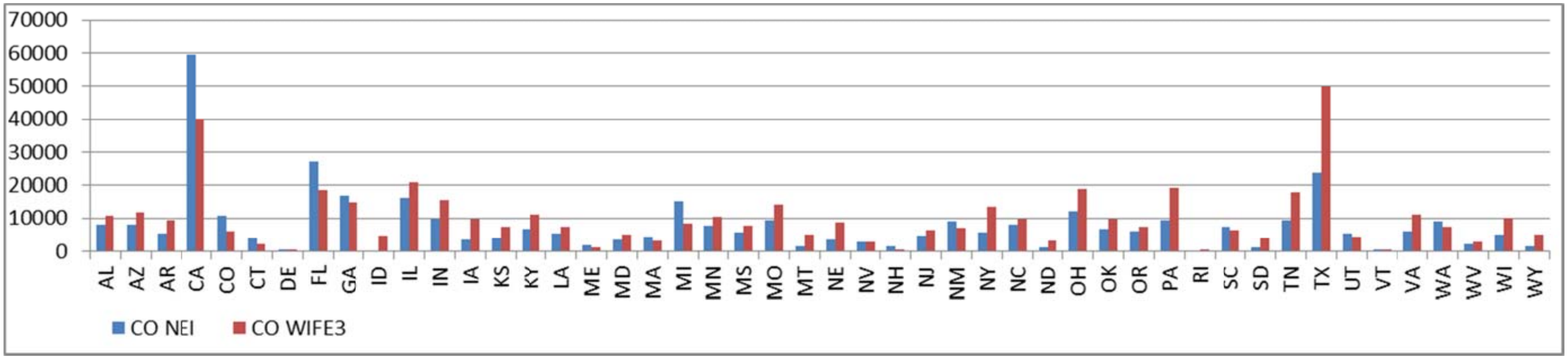

Figure 3 – Comparison of NEI and WIFE3 Emissions Estimate for 2008 (tons CO)

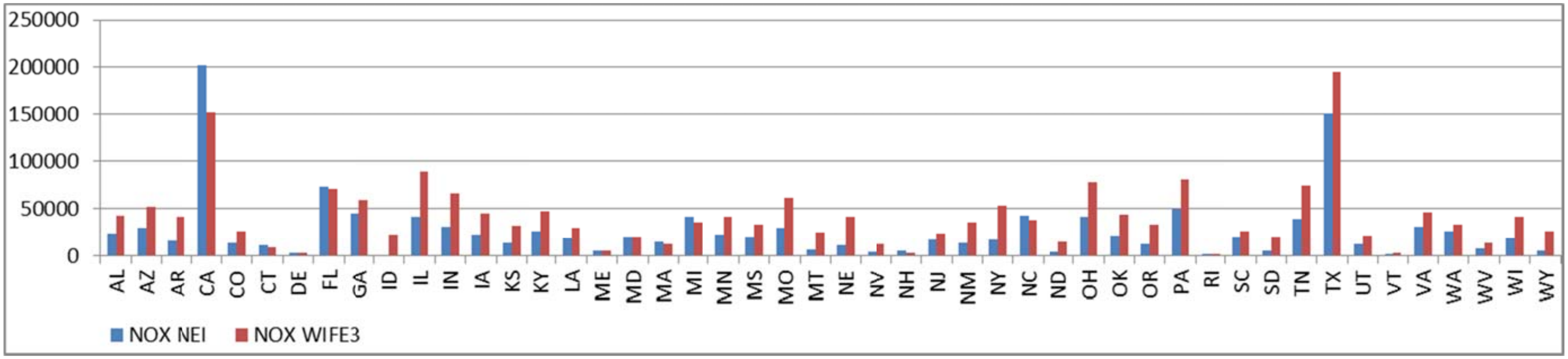

Figure 4 – Comparison of NEI and WIFE3 Emissions Estimate for 2008 (tons NOx)

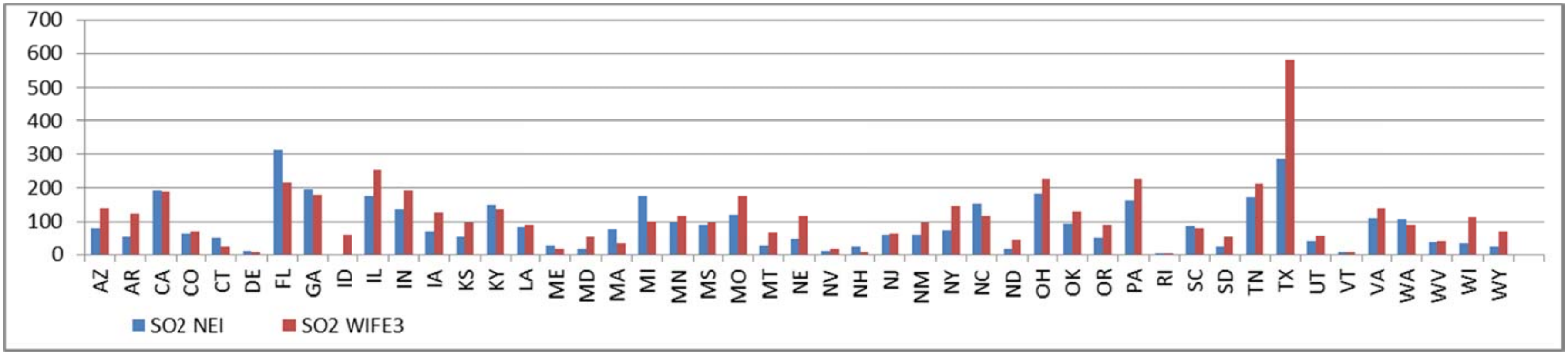

Figure 5 – Comparison of NEI and WIFE3 Emissions Estimate for 2008 (tons SO2)

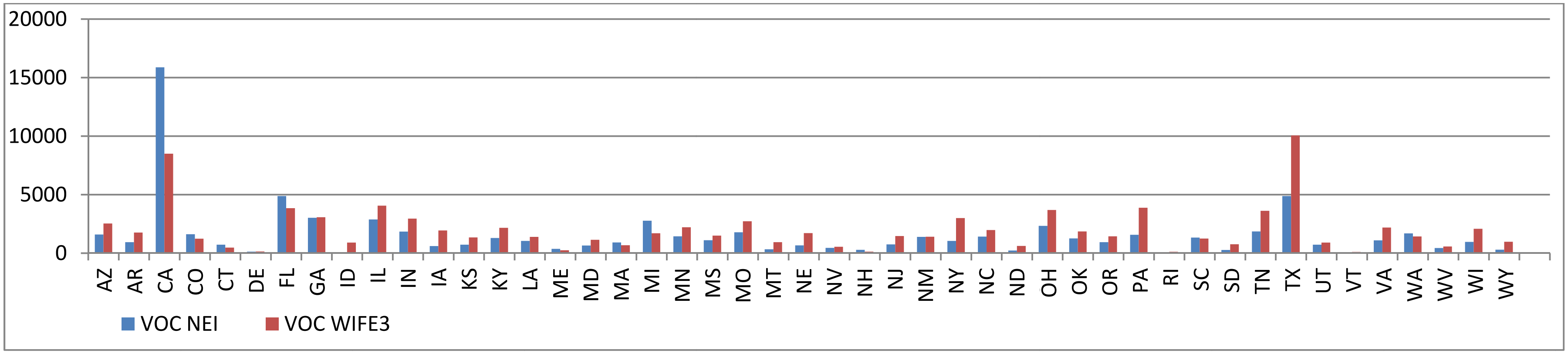

Figure 6 – Comparison of NEI and WIFE3 Emissions Estimate for 2008 (tons VOC)

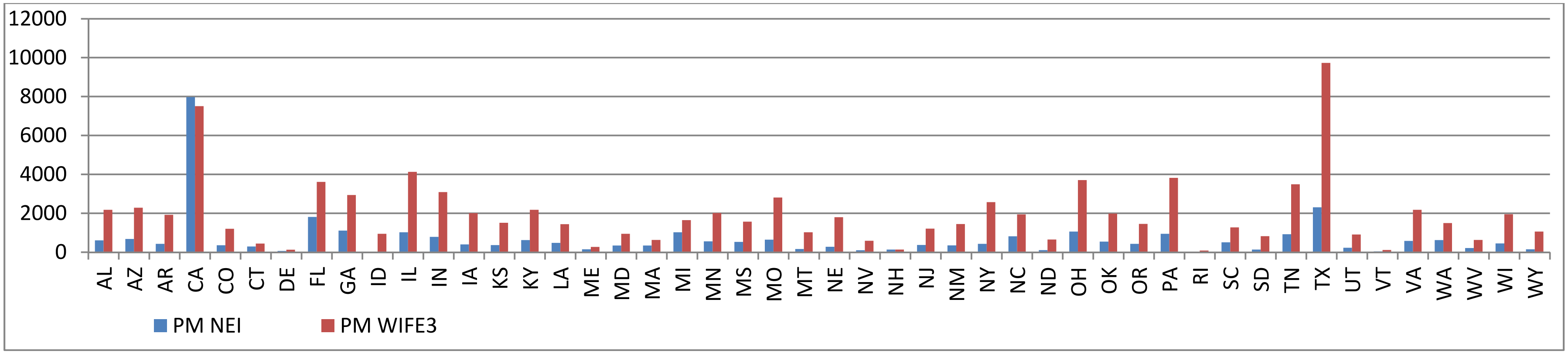

Figure 7 – Comparison of NEI and WIFE3 Emissions Estimate for 2008 (tons PM)

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