An Overview of Mobile Source Emissions and their Impacts on Air Quality and Climate

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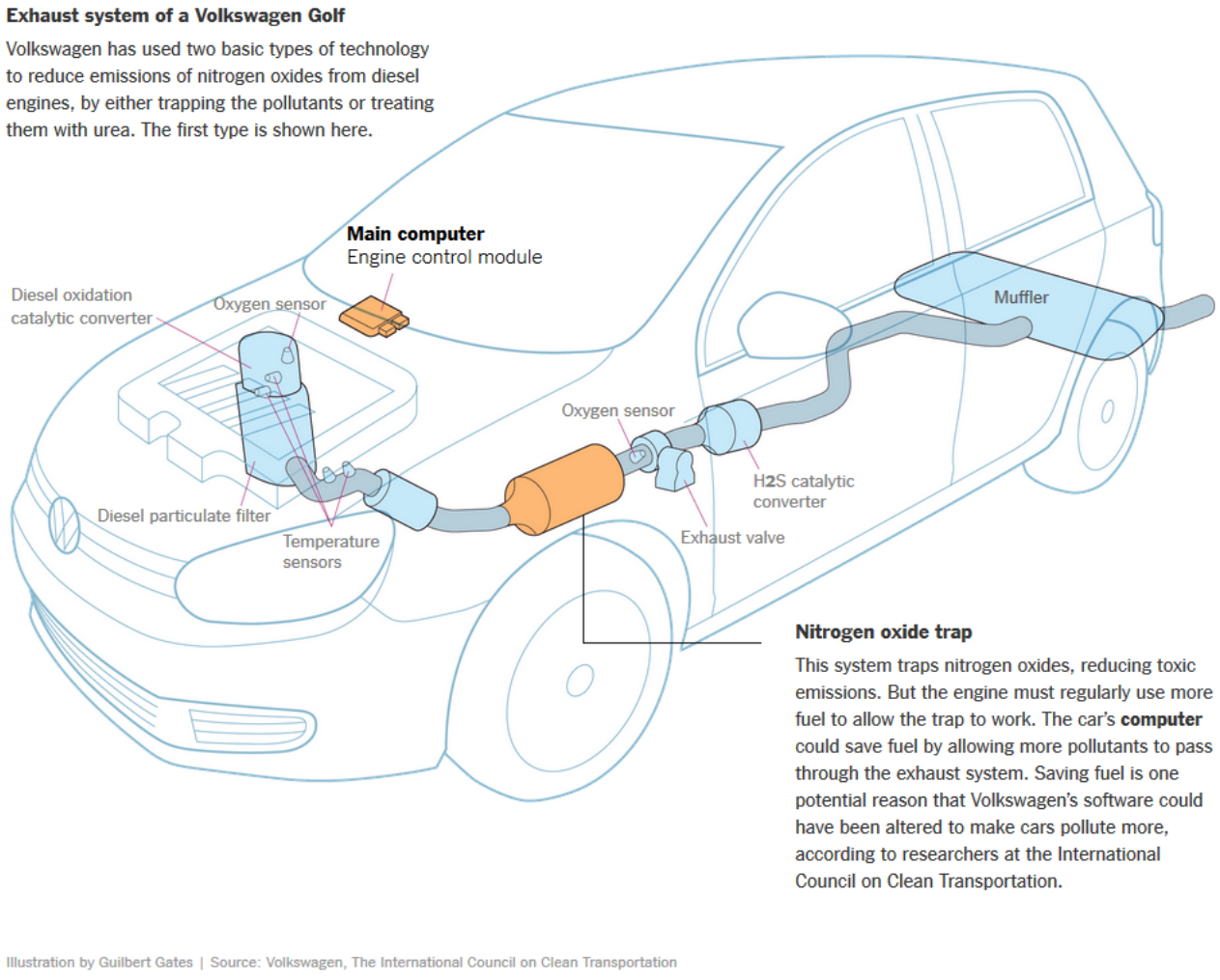
Timeline of the Volkswagen Scandal

May 2014
CARB and WVU researchers find VW diesels emit up to **40x** more NO_x than the standard

Sep. 18, 2015
VW scandal breaks to public, ordered to recall **482,000** vehicles in U.S.

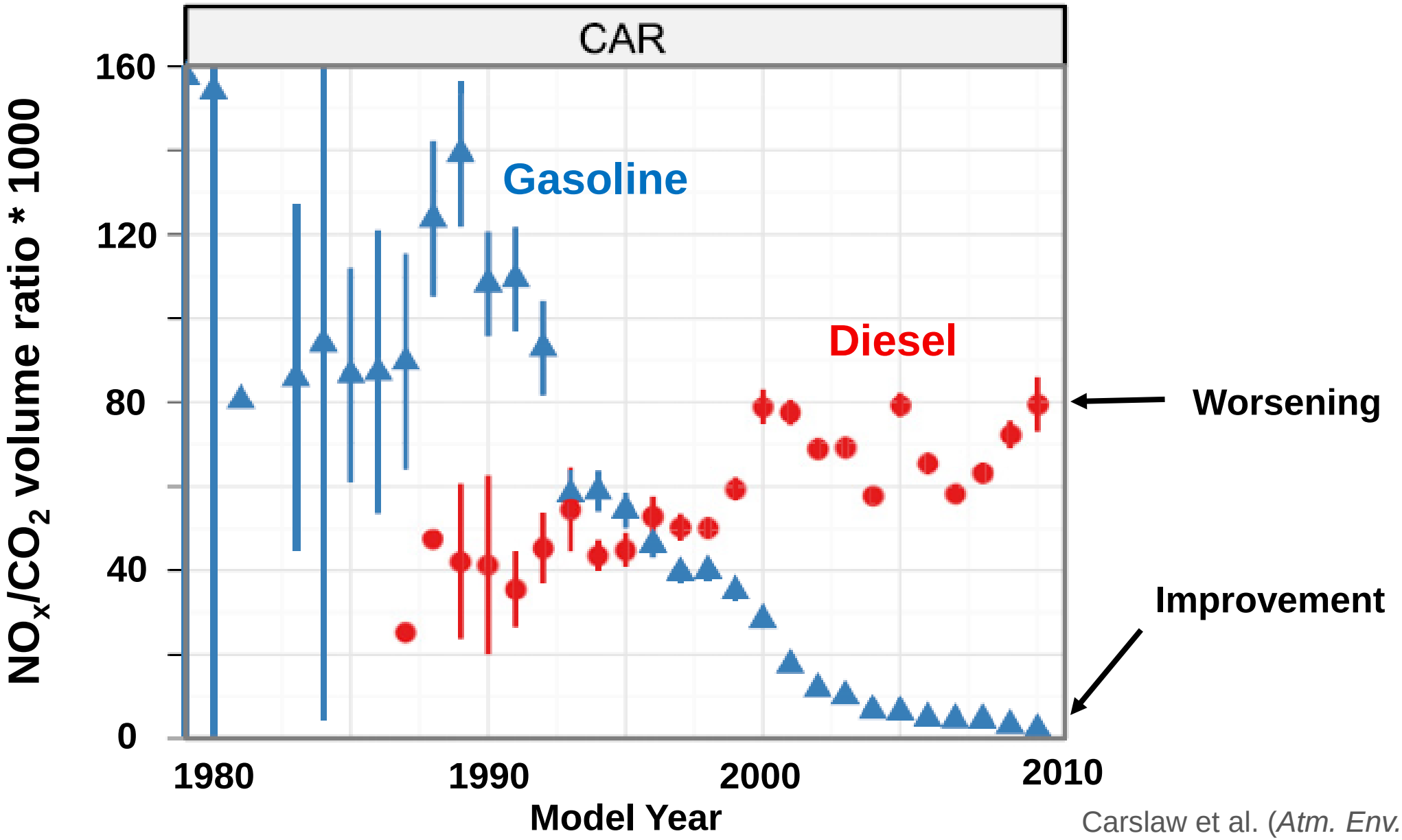
Oct. 15, 2015
VW to recall **8.5M** diesel cars across European Union

June 28, 2016
VW reaches U.S. settlement of **$14.7B**:
- $12,500 to $44,000 to repurchase cars
- $5,100 to $10,000 to fix cars
- $2.7B for environmental cleanup
- $2.0B for zero-emission vehicles



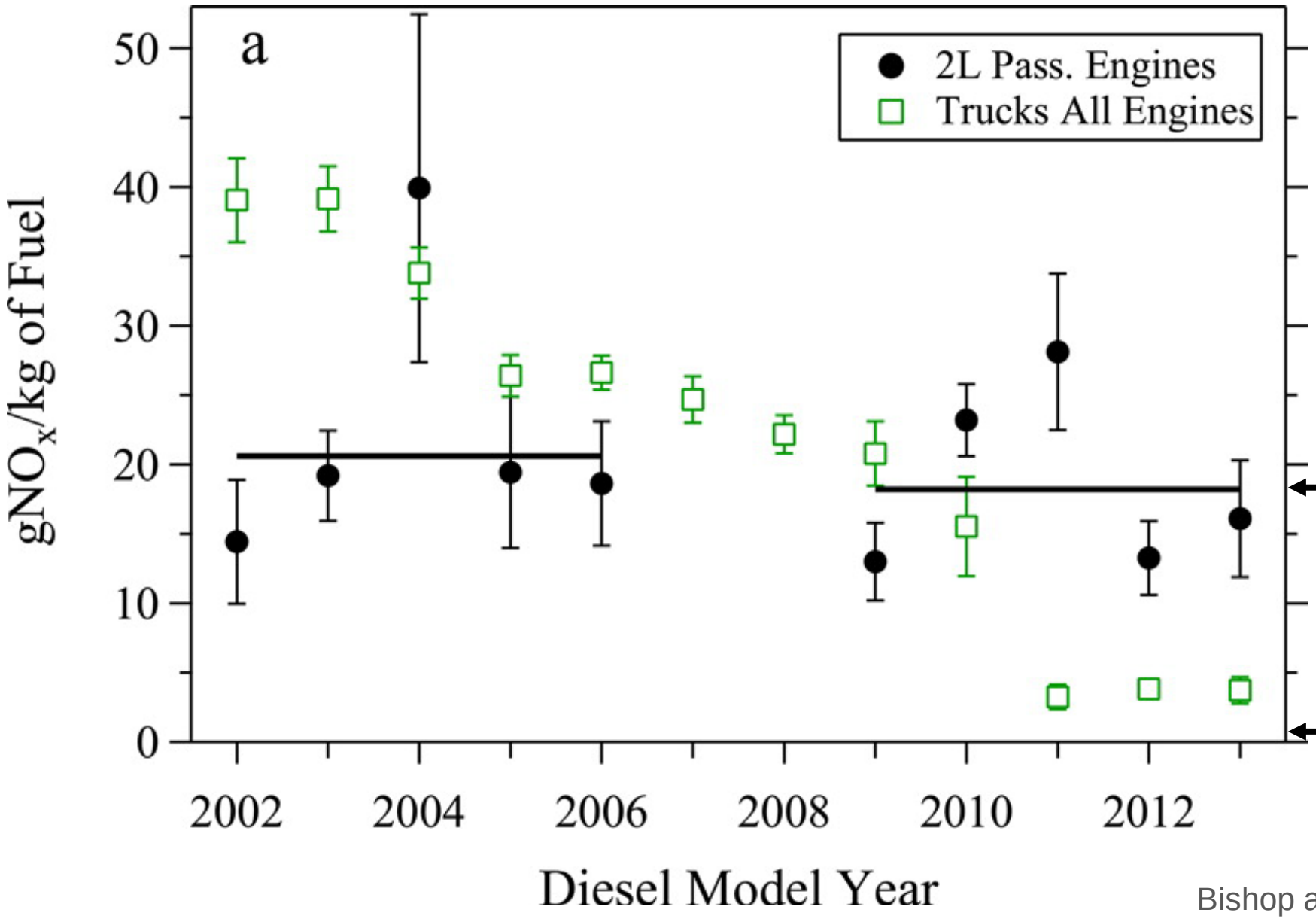
Sources: theGuardian (12/10/15), CNN (6/28/16), NYT (7/19/16)

European Trends in Passenger Vehicle NO_x Emission Factors



Carslaw et al. (*Atm. Env.* 2011)

U.S. Trends in Diesel Vehicle NO_x Emission Factors



Real-world vehicle fleet

New Car ~0.4 g/kg fuel

Bishop and Stedman (*Env. Sci. Technol.* 2015)

Case Study on Managing Air Quality and Climate Change

Are gasoline or diesel vehicles better for the environment?

Automobiles mostly gasoline-powered

Emission control technologies more robust (e.g., three-way catalytic converters)

Automobiles ~50% diesel (varies by country)

Improved fuel efficiency by ~30%

Overview of Lecture

(1) What are mobile sources and what do the emit?

(2) What is the impact of nitrogen oxide (NO_x) emissions on ozone (O_3)?

(3) How do gasoline and diesel engines impact aerosol concentrations?

(4) What is the pathway forward for sustainable transportation systems?

In US…

~70% CO

~50% Nitrogen Oxides

~50% Black Carbon

~30% CO_2

Mobile Sources are a major source of GHGs and air toxics

~600 coal-fired power plants
~1700 natural-gas plants

~230 million cars +
~3 million freight trucks

Challenge to estimate emissions

- Scale and mobility
- Not continuously monitored
- Vehicles evolving

Key Features of Gasoline and Diesel Engines

Gasoline Engine

Spark ignition
(octane: rated to avoid premature ignition)

Fuel comprised of
aromatics, branched-alkanes

Stoichiometric combustion,
air-fuel **pre-mixed**

Pollutants of concern:
CO, VOCs, NO_x

Diesel Engine

Compression ignition
(cetane: rated for ease of ignition)

Fuel comprised of
long-chain n-alkanes

Fuel lean combustion,
air-fuel **not pre-mixed**

Pollutants of concern:
NO_x, PM, aldehydes

Common Vehicle Emission Control Technologies

Gasoline Engine

Three-way catalytic converters

Oxidation of CO, VOCs → CO_2

Reduction of NO_x → N_2

Exhaust gas recirculation (EGR)

Lowers NO_x emissions

Positive crankcase ventilation

Control evaporative VOC emissions

Diesel Engine

Selective catalytic reduction systems

Reduction of NO_x → N_2 using urea

or NO_x lean trap

NO_x removed by adsorption, requires **regeneration**

Diesel oxidation catalyst

Oxidation of CO, VOCs → CO_2

Exhaust gas recirculation (EGR)

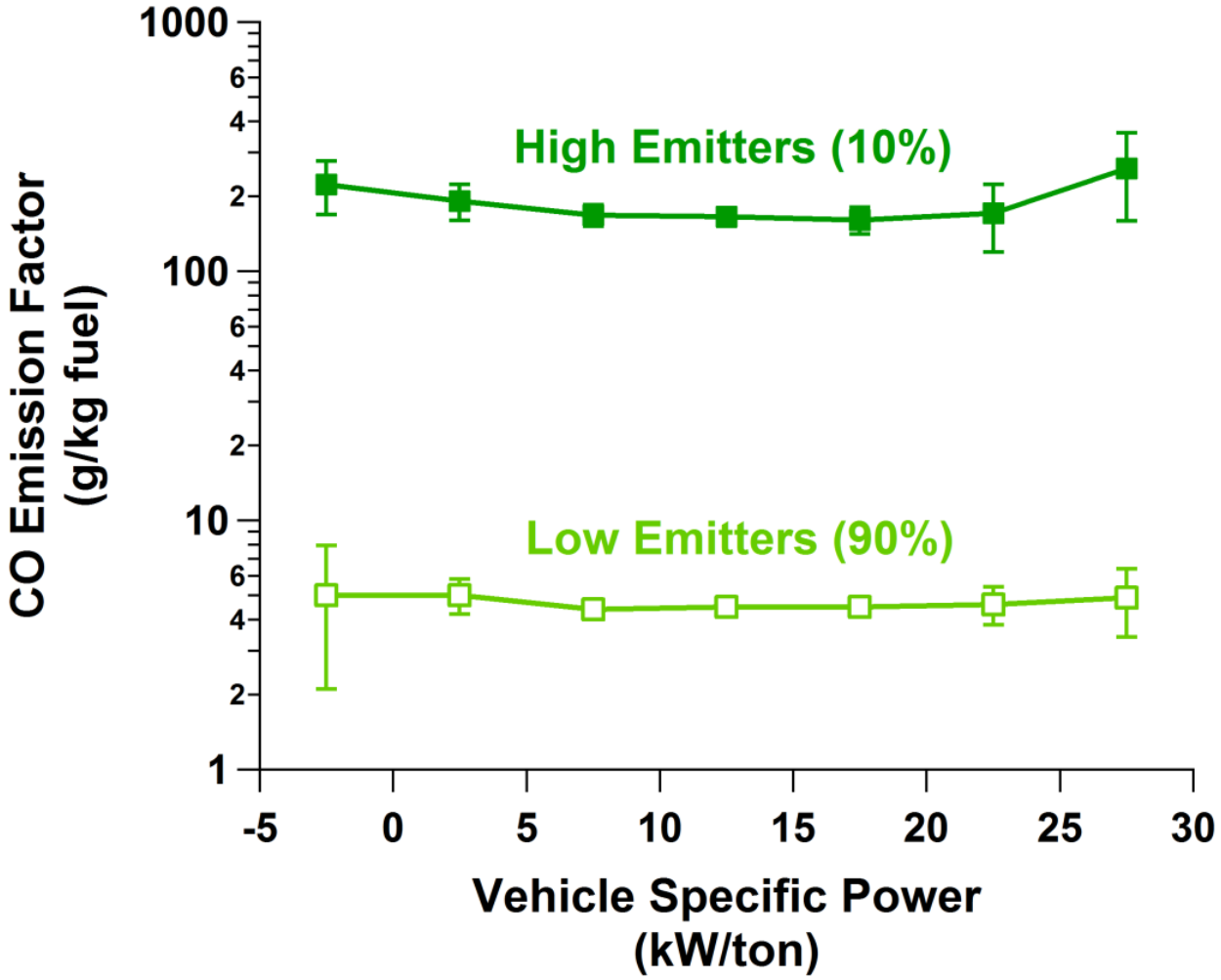
Lowers NO_x emissions

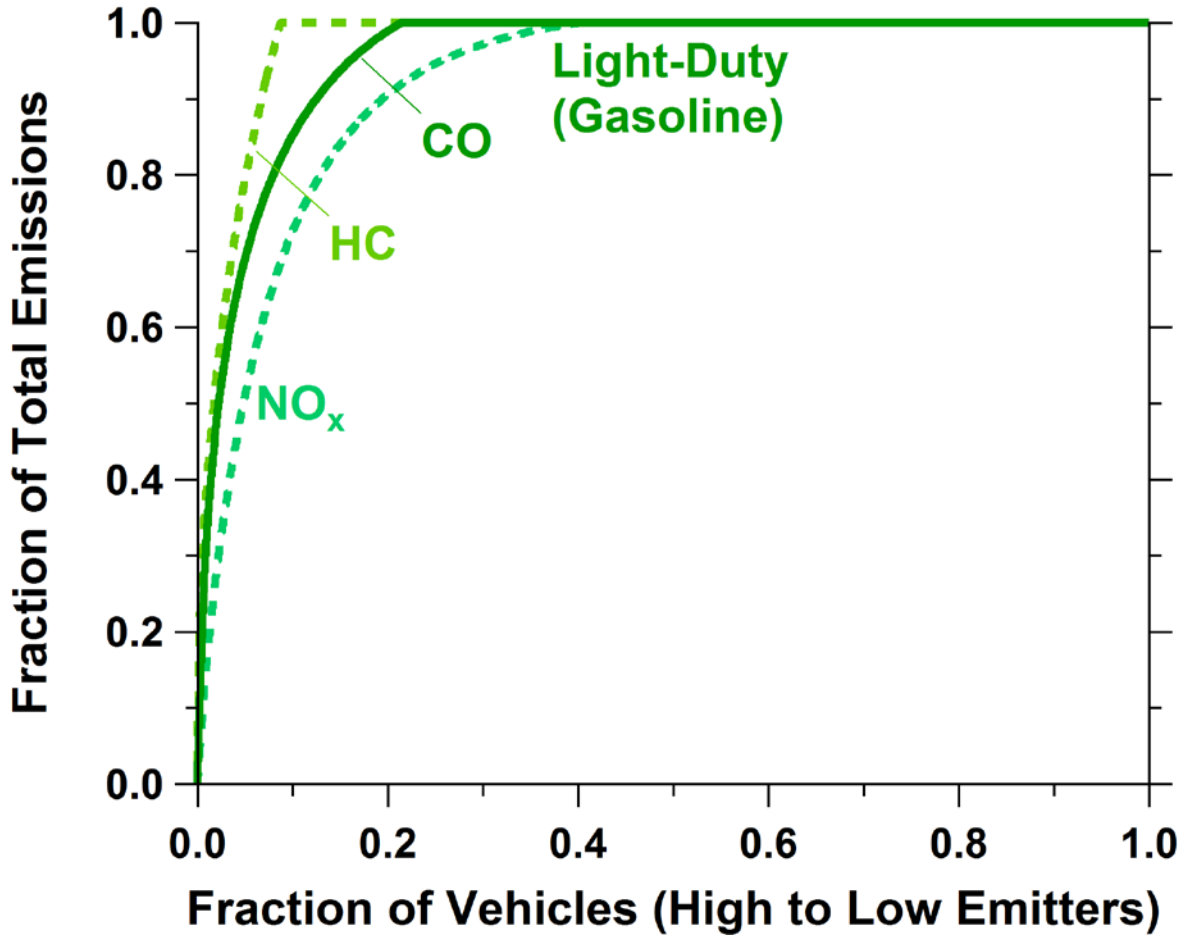
Diesel particle filters

Traps PM, requires **regeneration**

Super-Emitting Vehicles Account for Largest Share of Emissions

Emissions equipment only effective when they work as intended.





McDonald et al. (*Environ. Sci. & Technol.* 2013)

Long History of Inaccurate Transportation Emission Inventories

Many studies have identified problems with vehicle emission models

- Singer and Harley, *AE* 2000; Parrish et al., *AE* 2006; Lindhjem et al., *JAWMA* 2012; McDonald et al., *JGR* 2012; Anderson et al., *AE* 2014

Issues include:

- Changing methodologies
- Wrong emission trends and magnitudes
- Incorrect VOC speciation

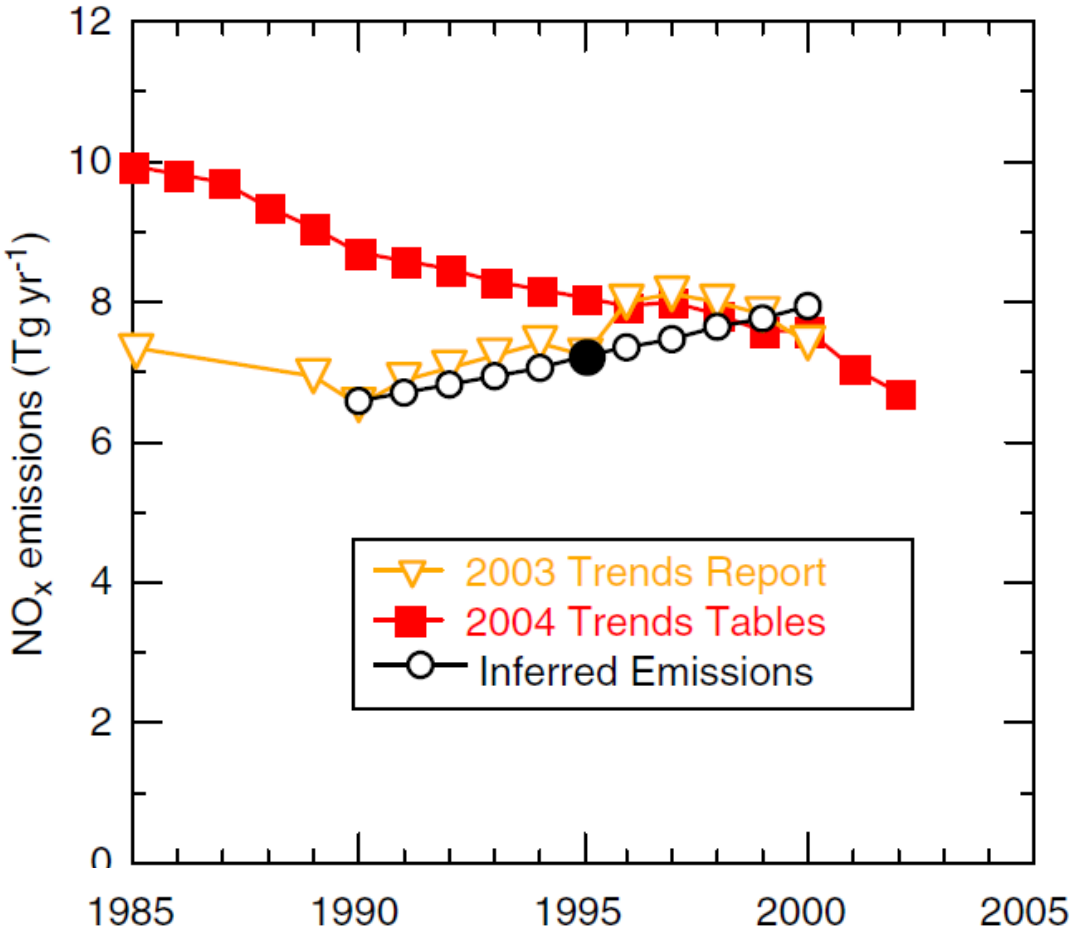
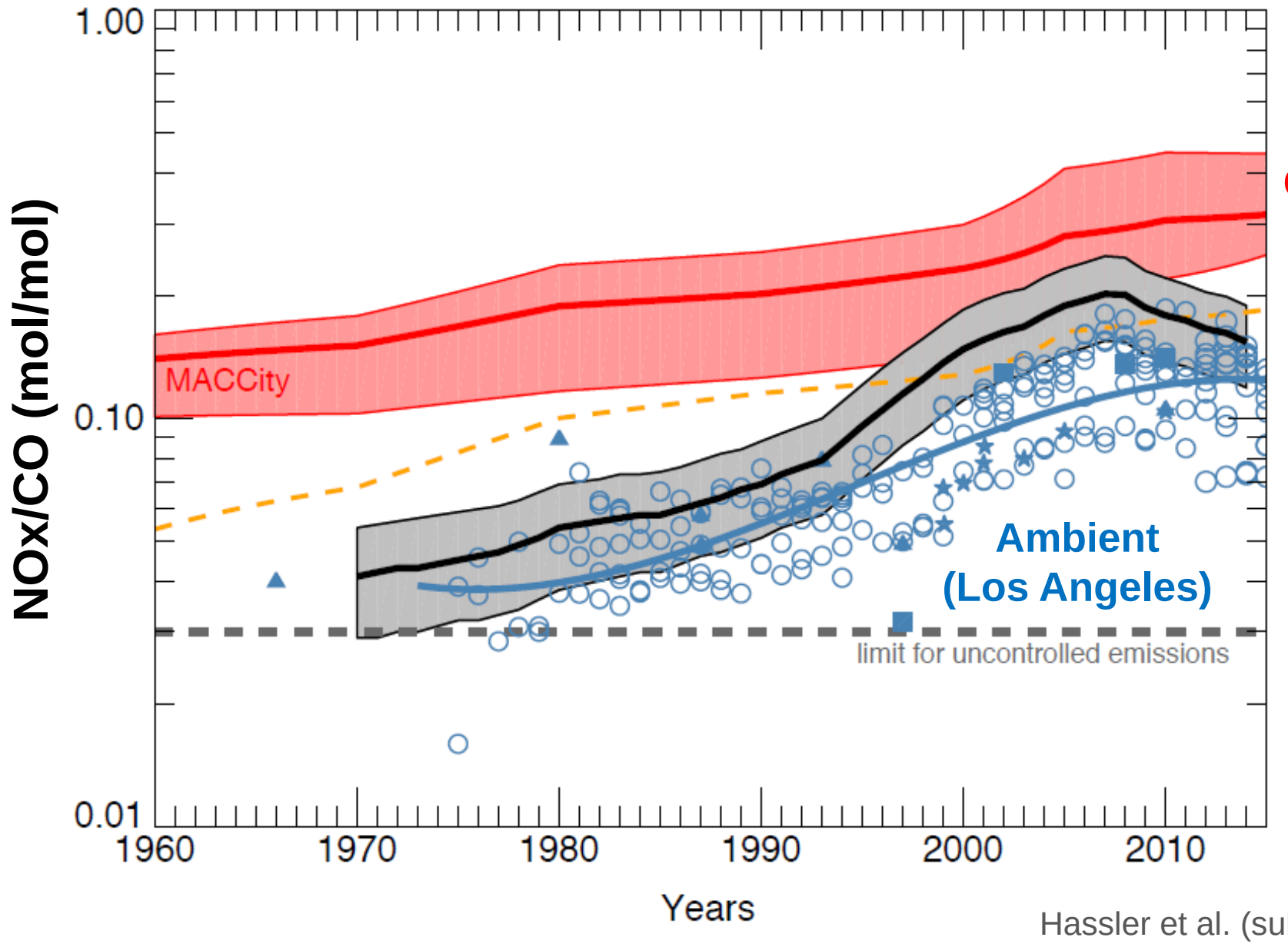


Figure from Parrish *Atm. Env.* 2006, "Critical evaluation of U.S. on-road vehicle emission inventories."

Also Discrepancies with a Global Emissions Inventory



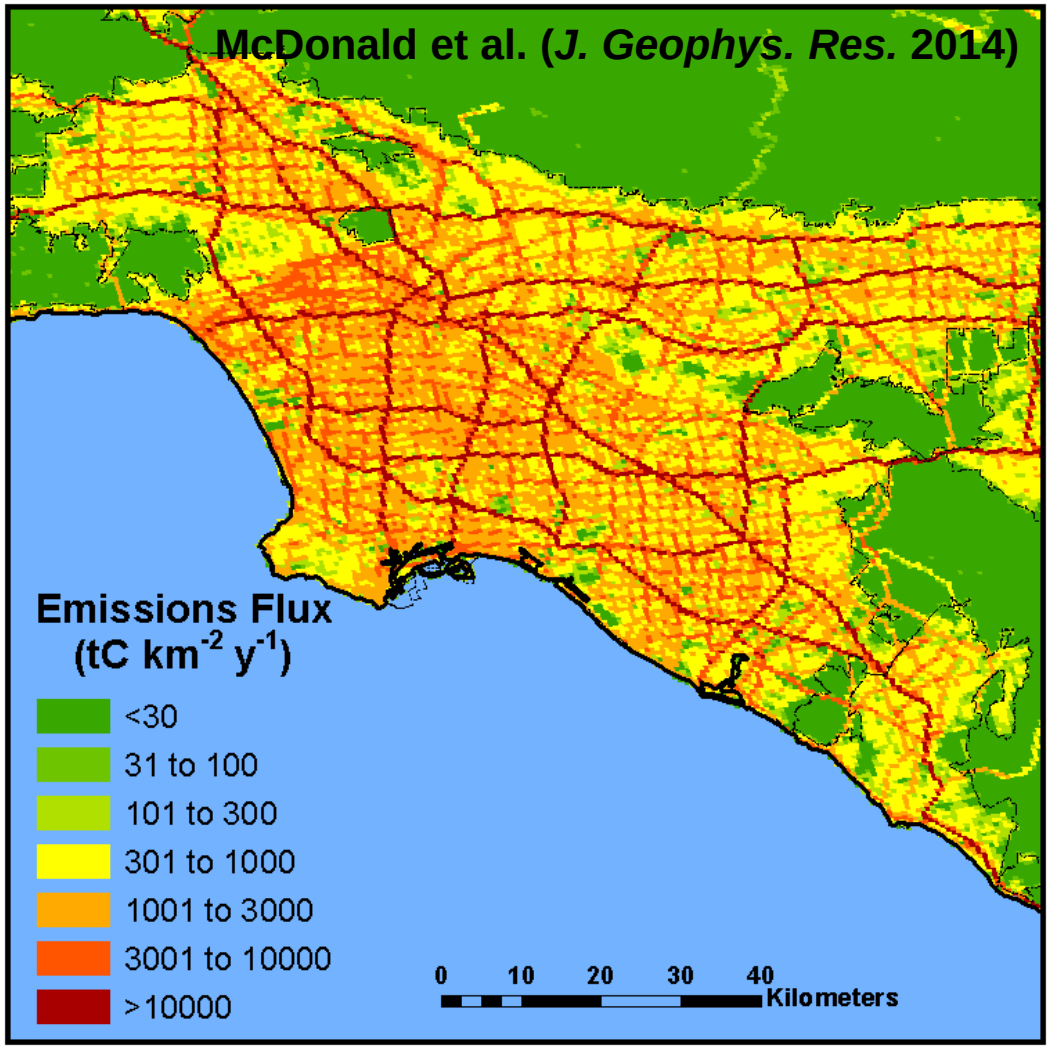
Global Inventory (Urban)

Mobile Source Emissions (This Study)

Hassler et al. (submitted *Geophys. Res. Let.*)

Building a Fuel-Based Vehicle Emissions Inventory

Emissions = Activity (kg fuel) **x Emission Factor** (g/kg fuel)



Quantify on-road CO_2 emissions

- State-level taxable gasoline and diesel fuel sales reports
- Public and annual

Map on-road CO_2 emissions

- Using traffic count data
- Basis for scaling co-emitted combustion byproducts

Use of Roadway Studies for Emission Factors

Emissions = Activity (kg fuel) **x Emission Factor** (g/kg fuel)

Roadside monitoring data

- Measures in-use vehicles
- Captures high-emitters
- Regulatory models typically rely on chassis dynamometer tests

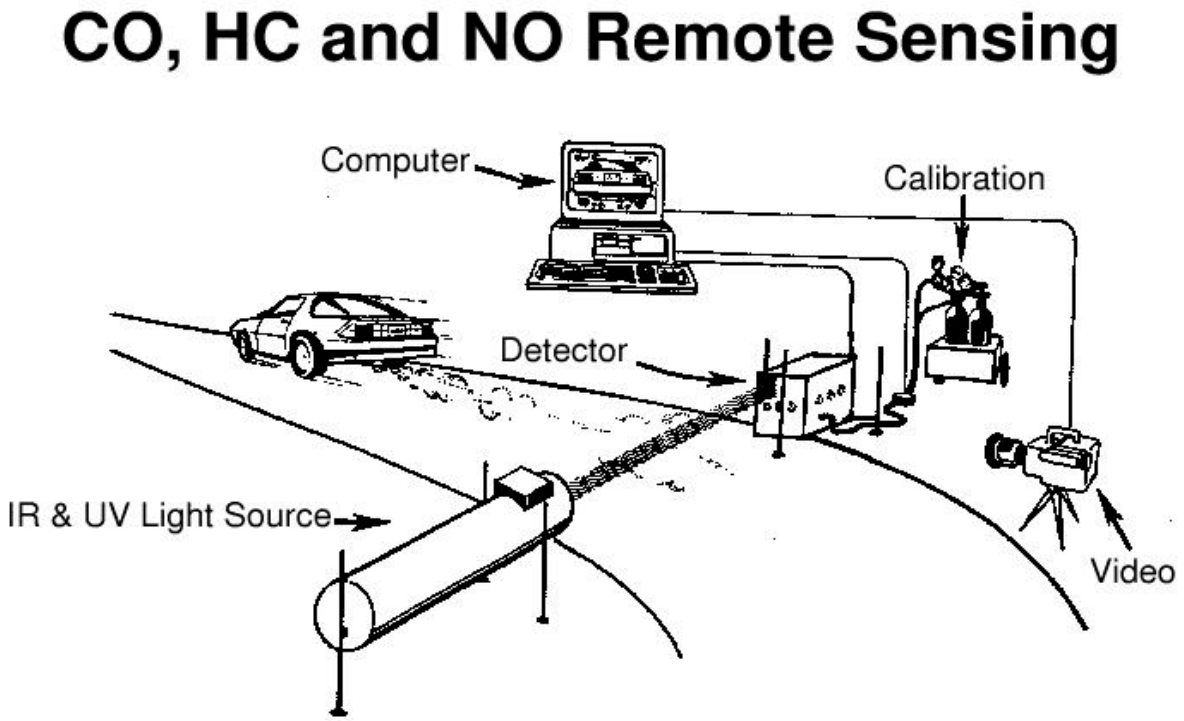


Figure from Univ. of Denver FEAT System

Long-Term Trends in U.S. On-Road NO_x Emission Factors

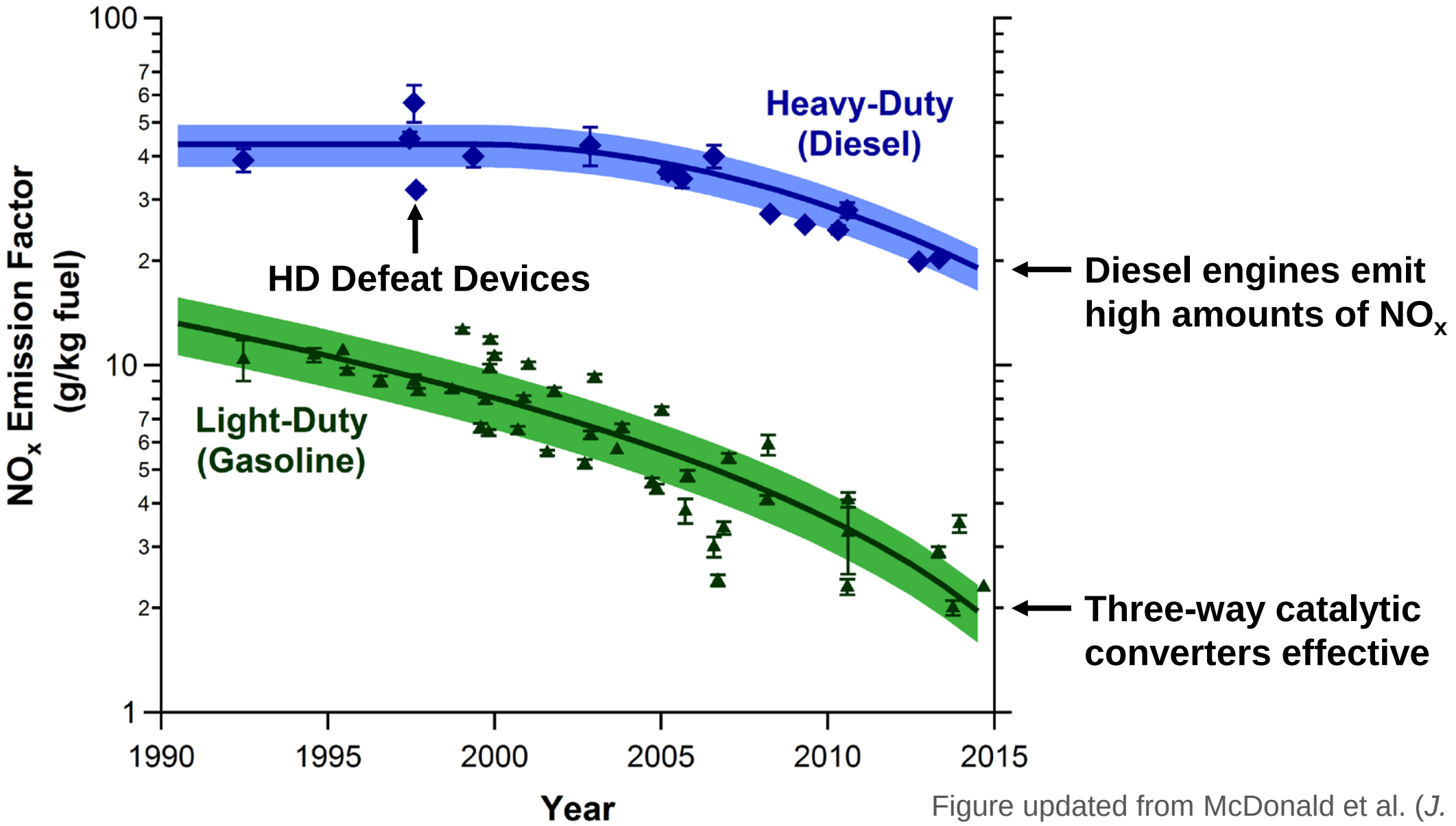
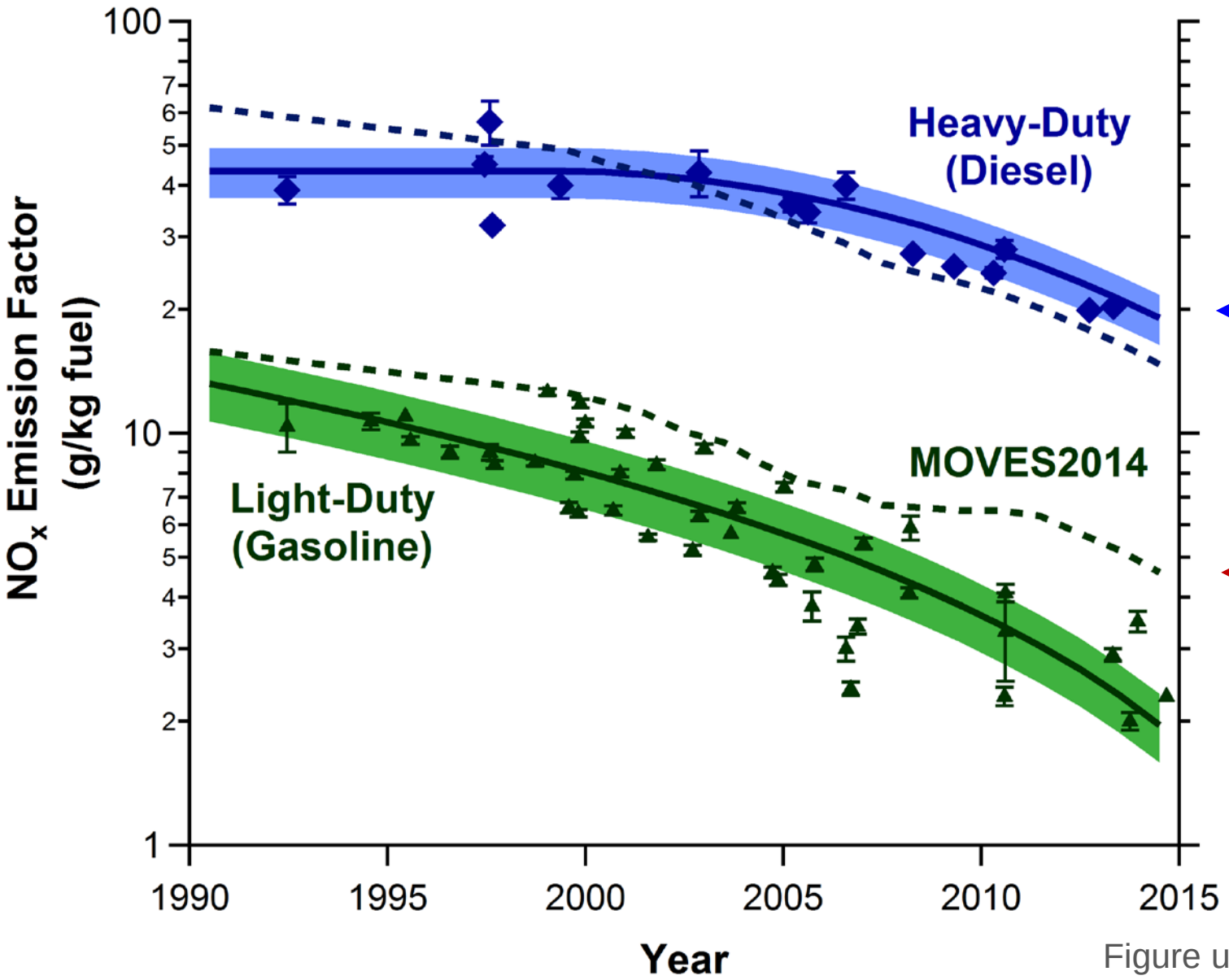


Figure updated from McDonald et al. (*J. Geophys. Res.* 2012)

Comparison with Current EPA Vehicle Emissions Model (MOVES)

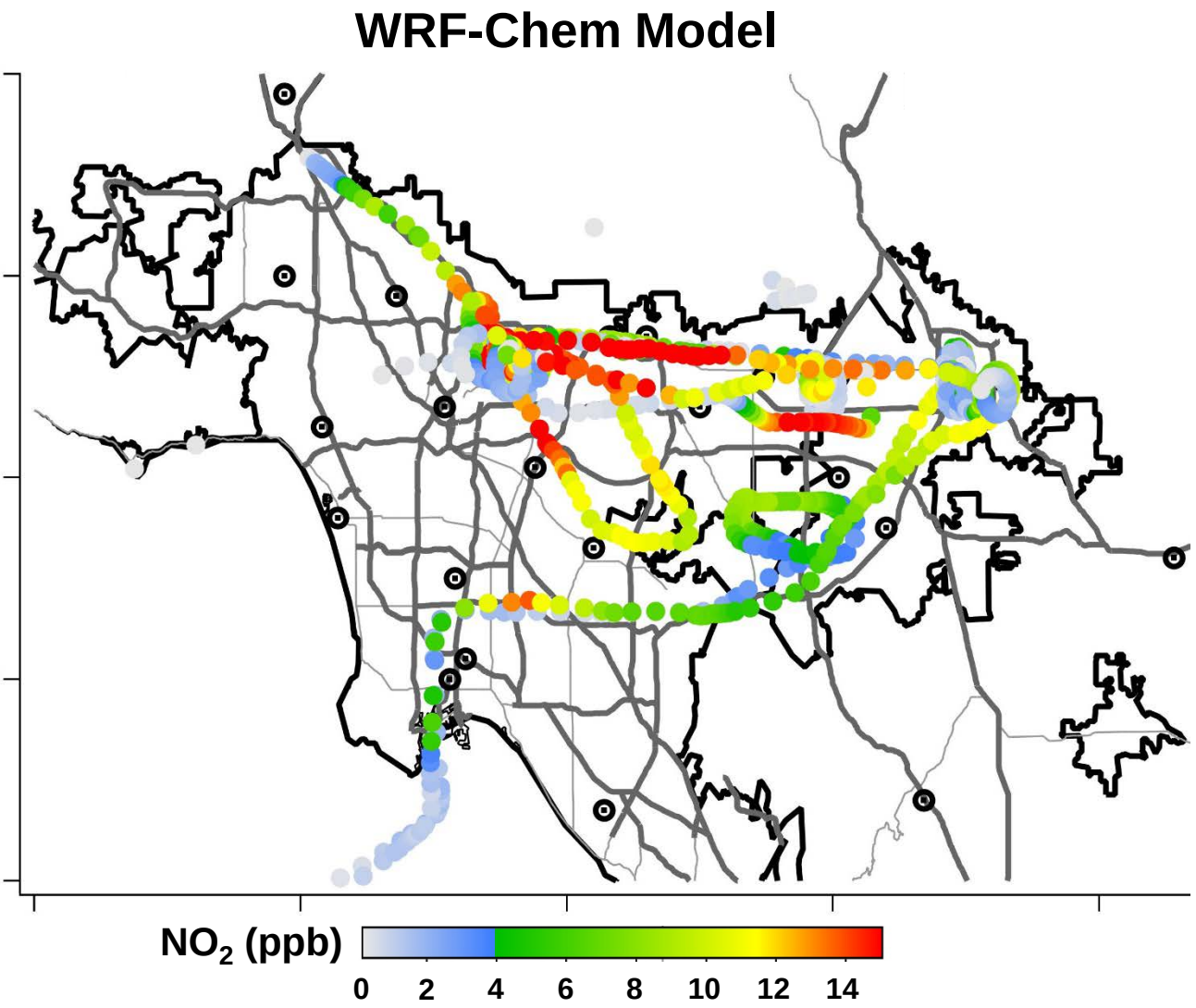


Diesel EF within ~20%

Gasoline EF high by factor of ~2

Figure updated from McDonald et al. (*J. Geophys. Res.* 2012)

Test of New NO_x Inventory against Aircraft Data (Los Angeles)

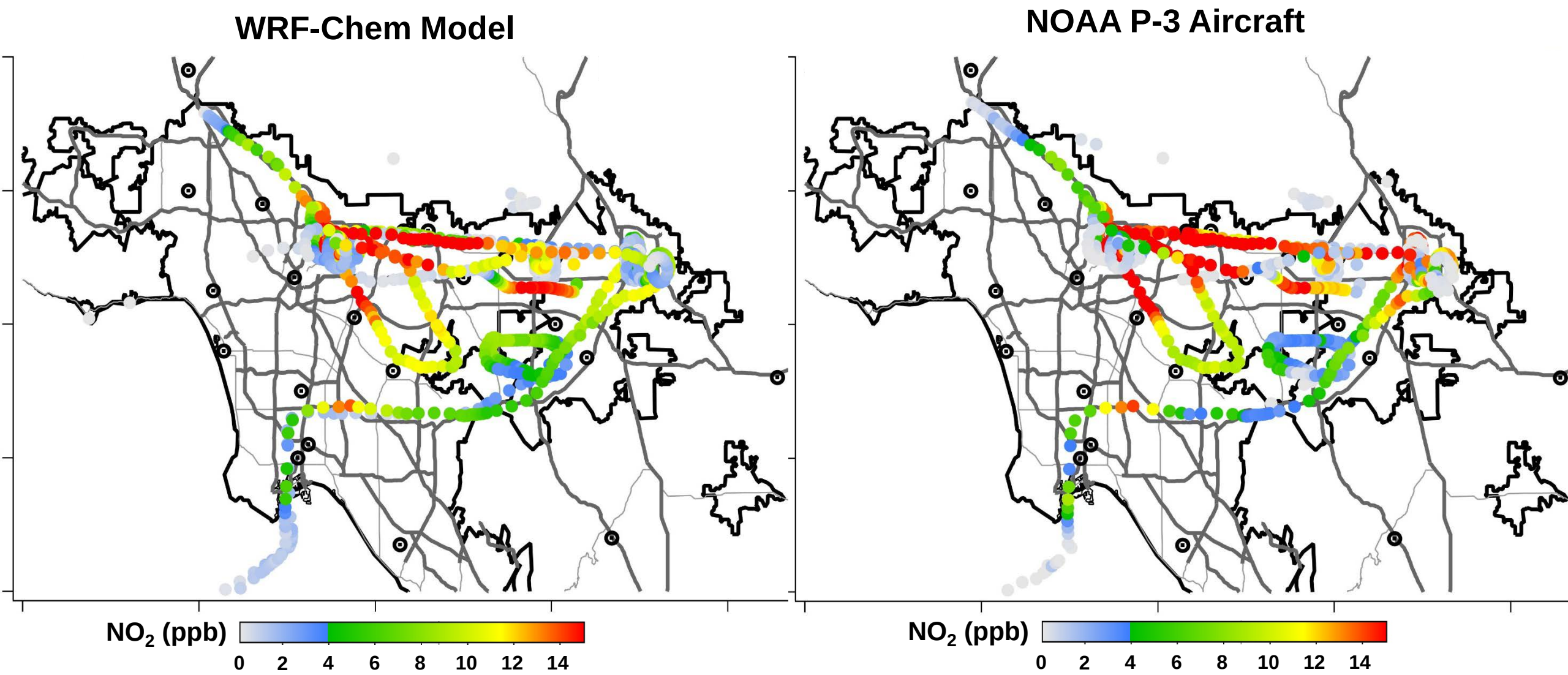


Simulated for California Nexus Study (CalNex) in 2010

- LA good test case of transportation emissions (~2/3 of NO_x budget)

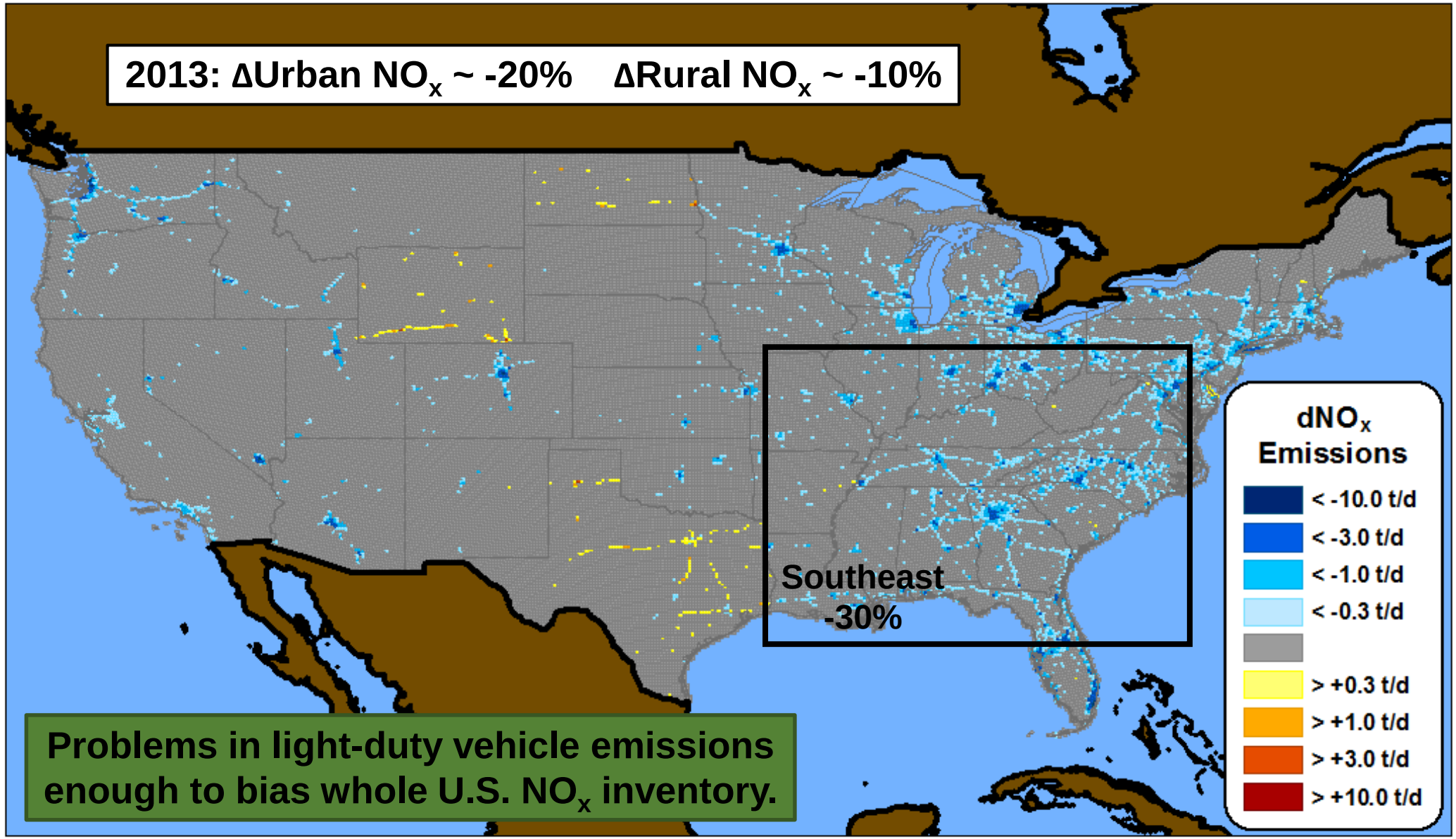
Kim et al. (*J. Geophys. Res.* 2016)

Strong Agreement between Model and Aircraft Observations



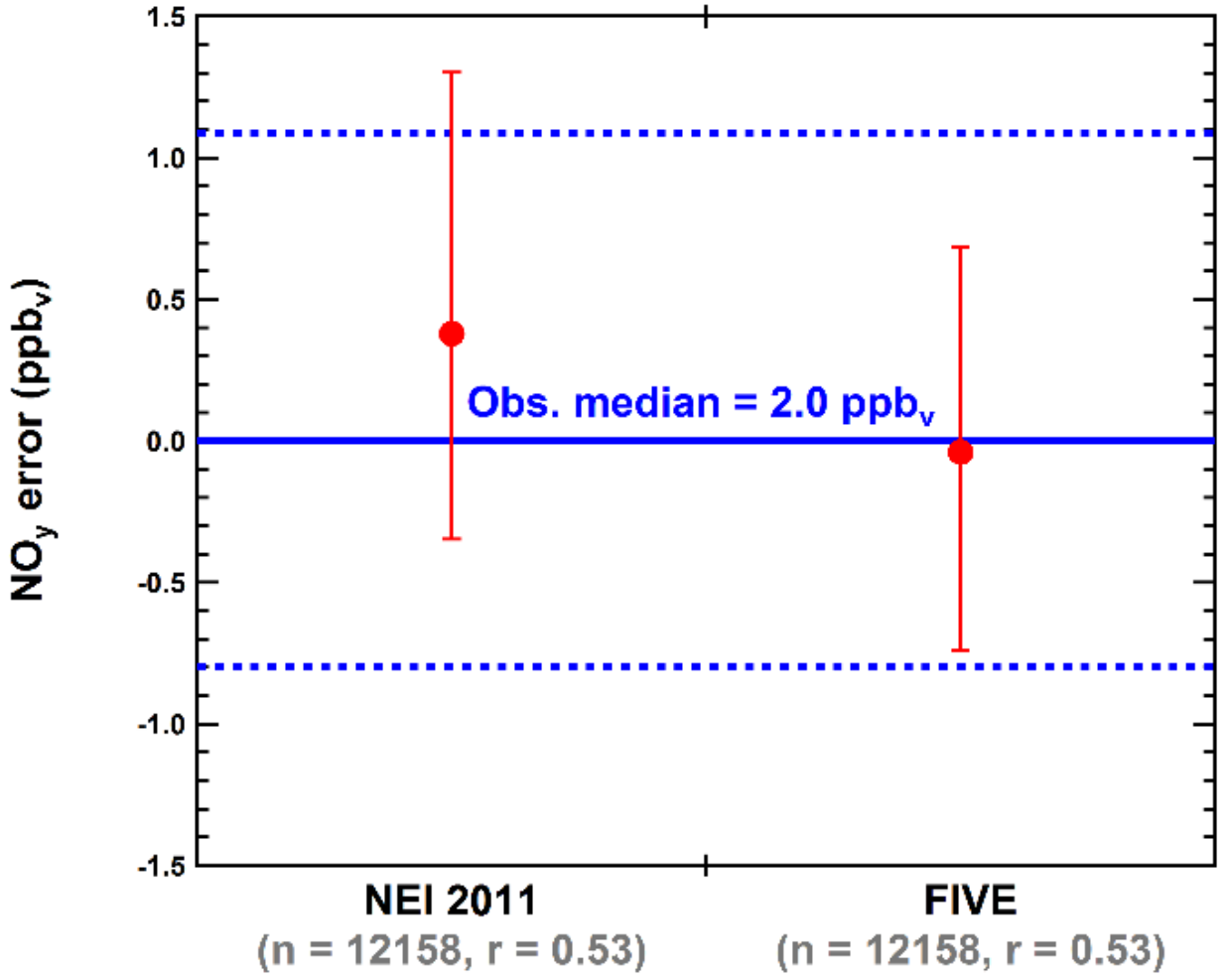
Kim et al. (*J. Geophys. Res.* 2016)

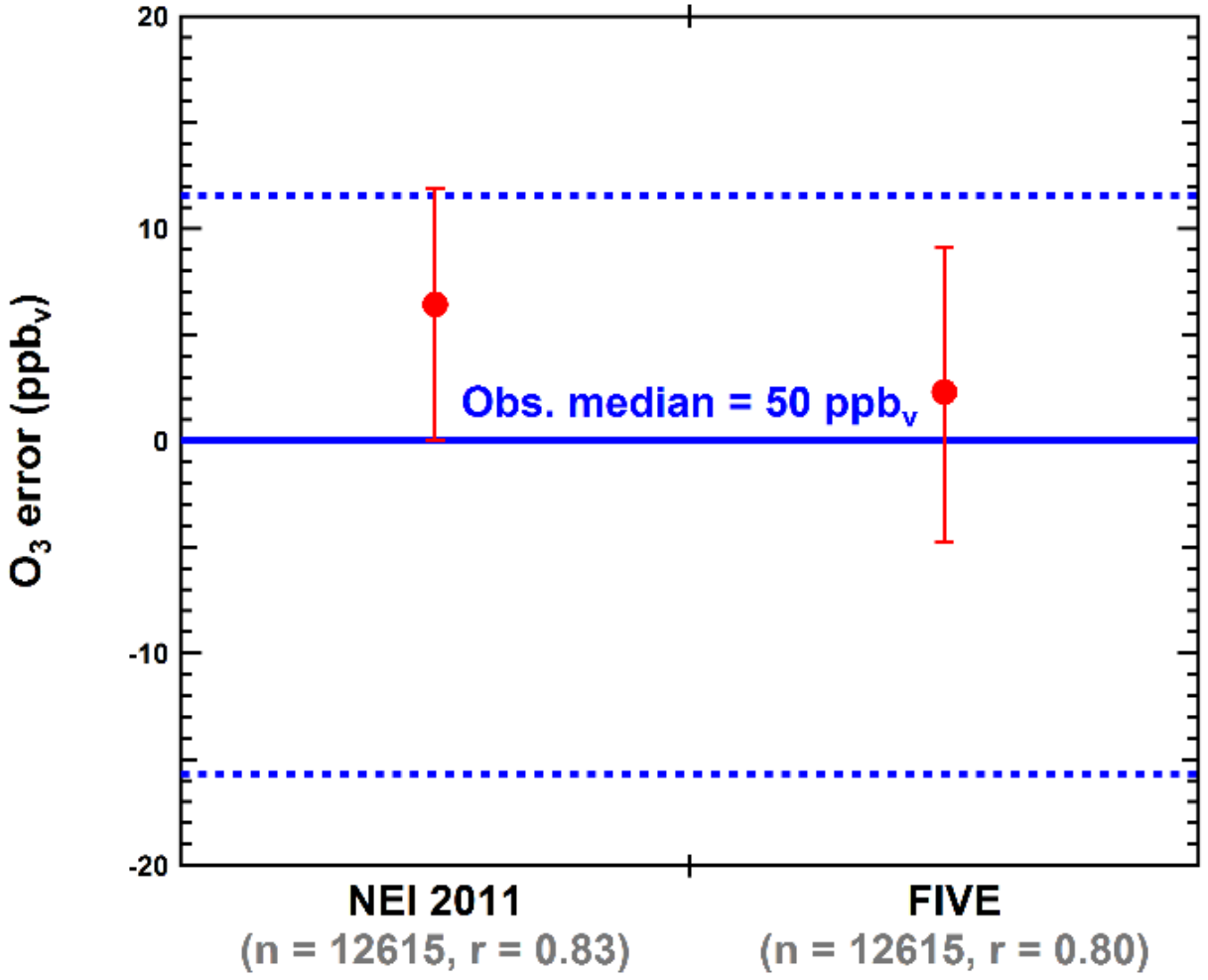
Difference in Total U.S. NO_x Emissions (Fuel-Based – EPA)



Model vs. Southeast Nexus Study Aircraft Observations (18 flights)

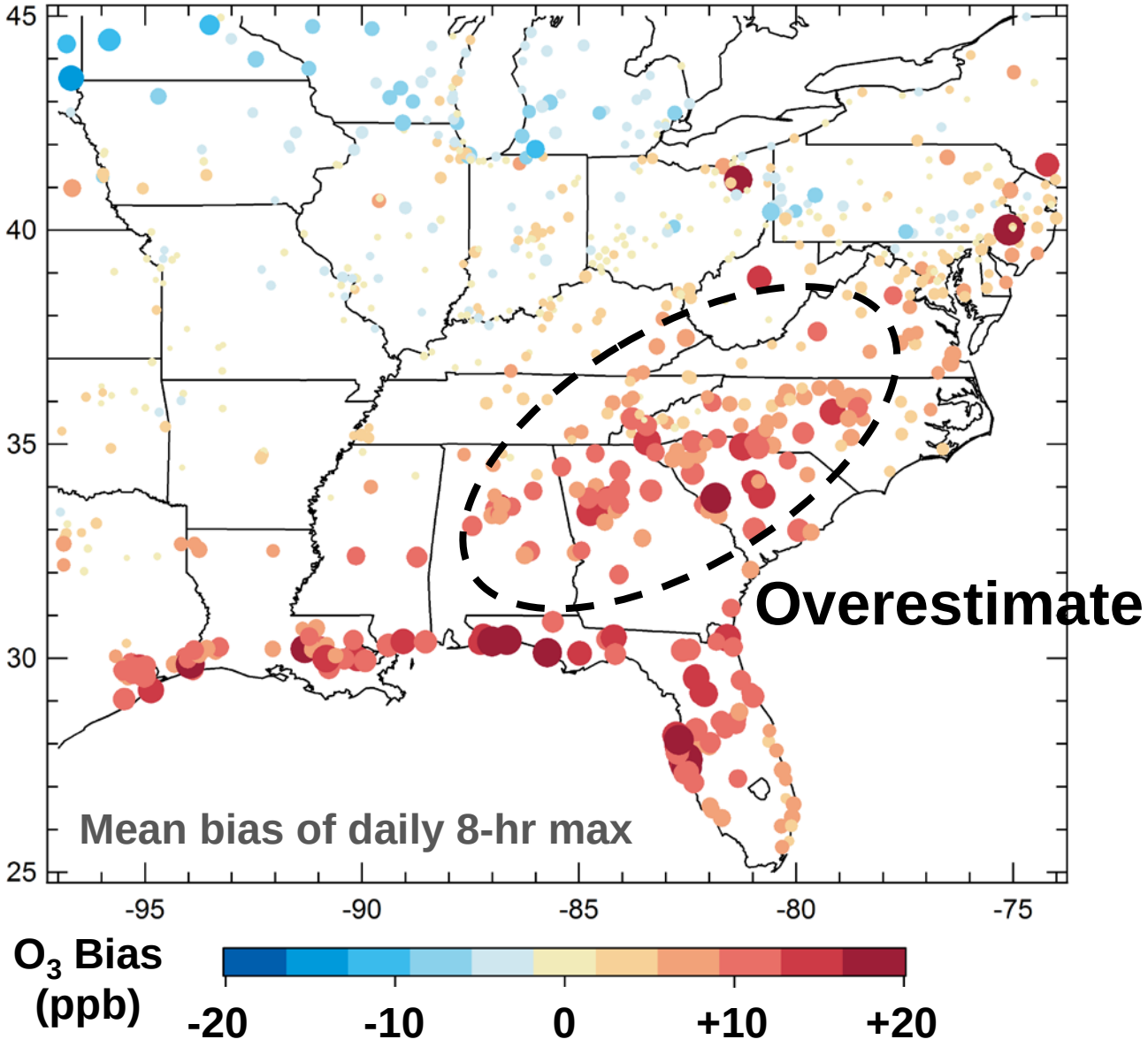
Comparisons windowed to boundary layer (200-700 m) and daytime (10 AM-6 PM CDT)





McDonald et al. (*in preparation*)

Large Biases in Ozone Models for the Eastern US

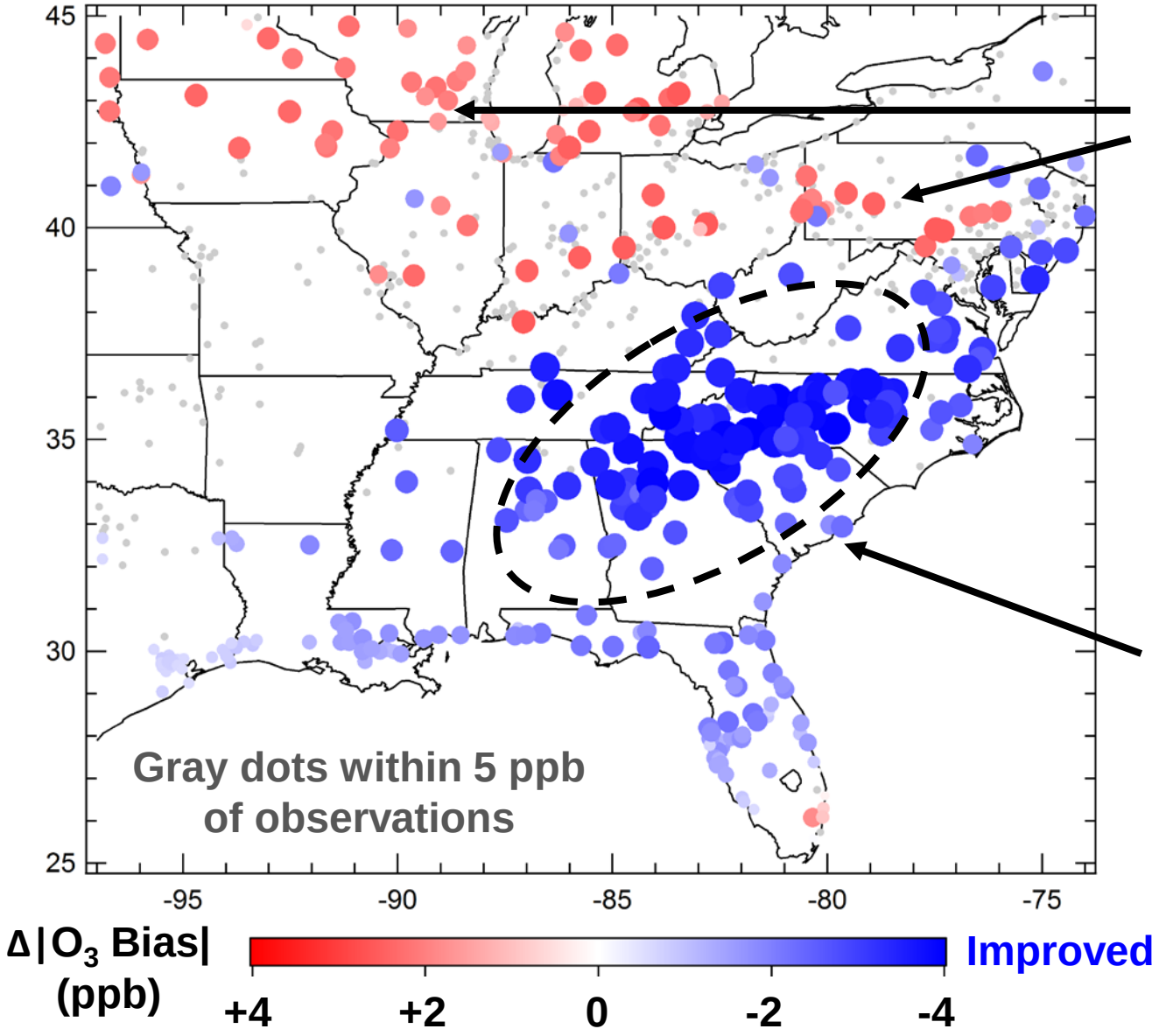


Simulation during Southeast Nexus Study (2013)

- Base case modeled using U.S. EPA's National Emissions Inventory 2011
- Includes biogenic emissions (BEIS v3.14)
- Model results evaluated with air quality monitoring station data

McDonald et al. (*in preparation*)

Significant Change in Ozone when Modeling Fuel-Based Inventory



May indicate importance of other sources of NO_x emissions

e.g. oil & gas, agriculture

Overall improvement in ozone prediction

McDonald et al. (*in preparation*)

U.S. 8-hr Ozone Standard Recently Lowered from 75 to 70 ppb (2015)

Health Professionals across the Nation Urge EPA to Finalize Most Protective Ozone Air Quality Standard

"According to EPA, a standard of 60 ppb would prevent up to 7,900 premature deaths and 1.8 million childhood asthma attacks in 2015 alone."

AMERICAN LUNG ASSOCIATION.

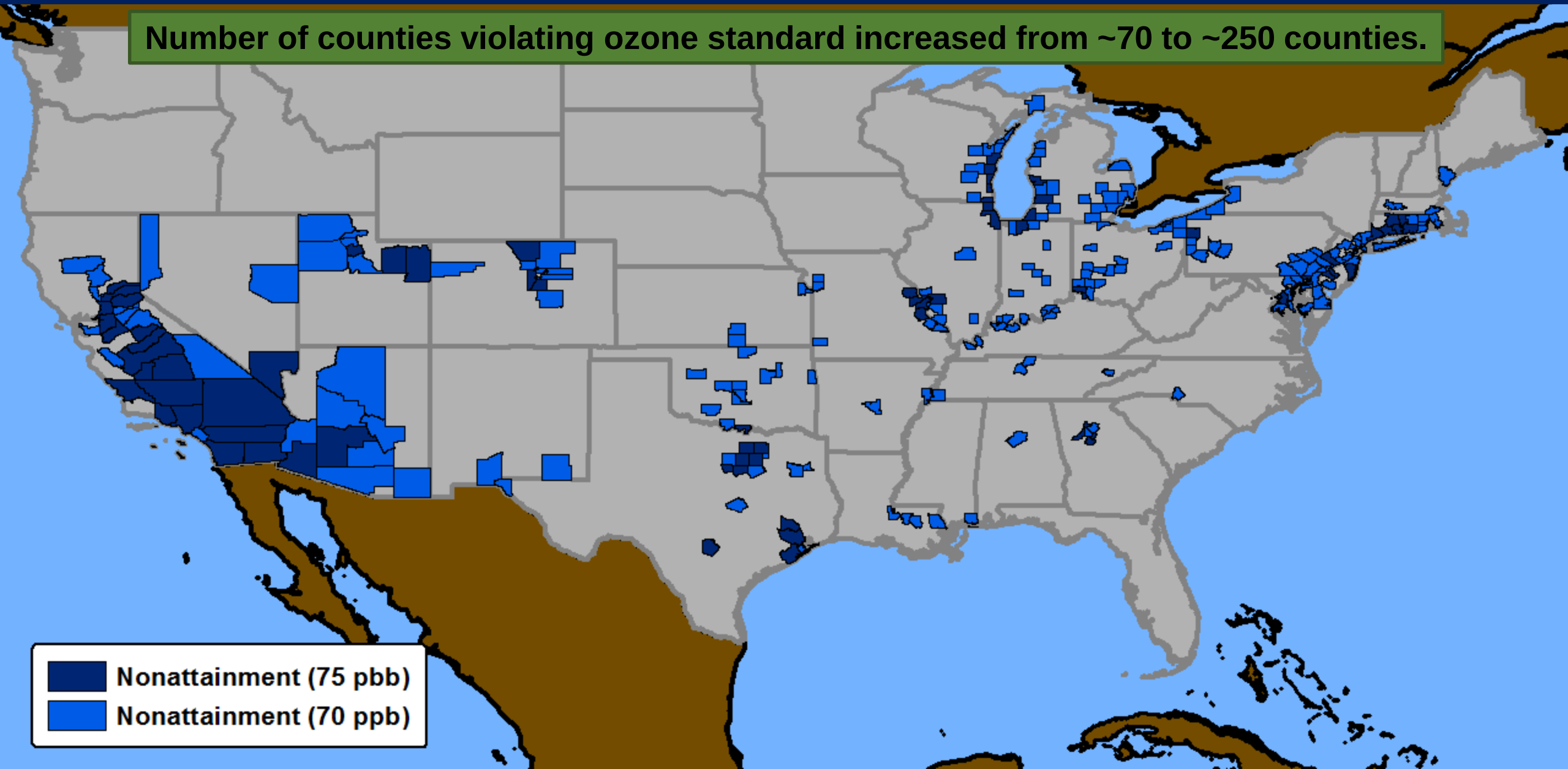
NATIONAL ASSOCIATION OF Manufacturers

*"Coloradans want and deserve **clean air**…while growing Colorado's **economy**. At the same time, the EPA must recognize the unique **challenges**…to the Rocky Mountain West."*

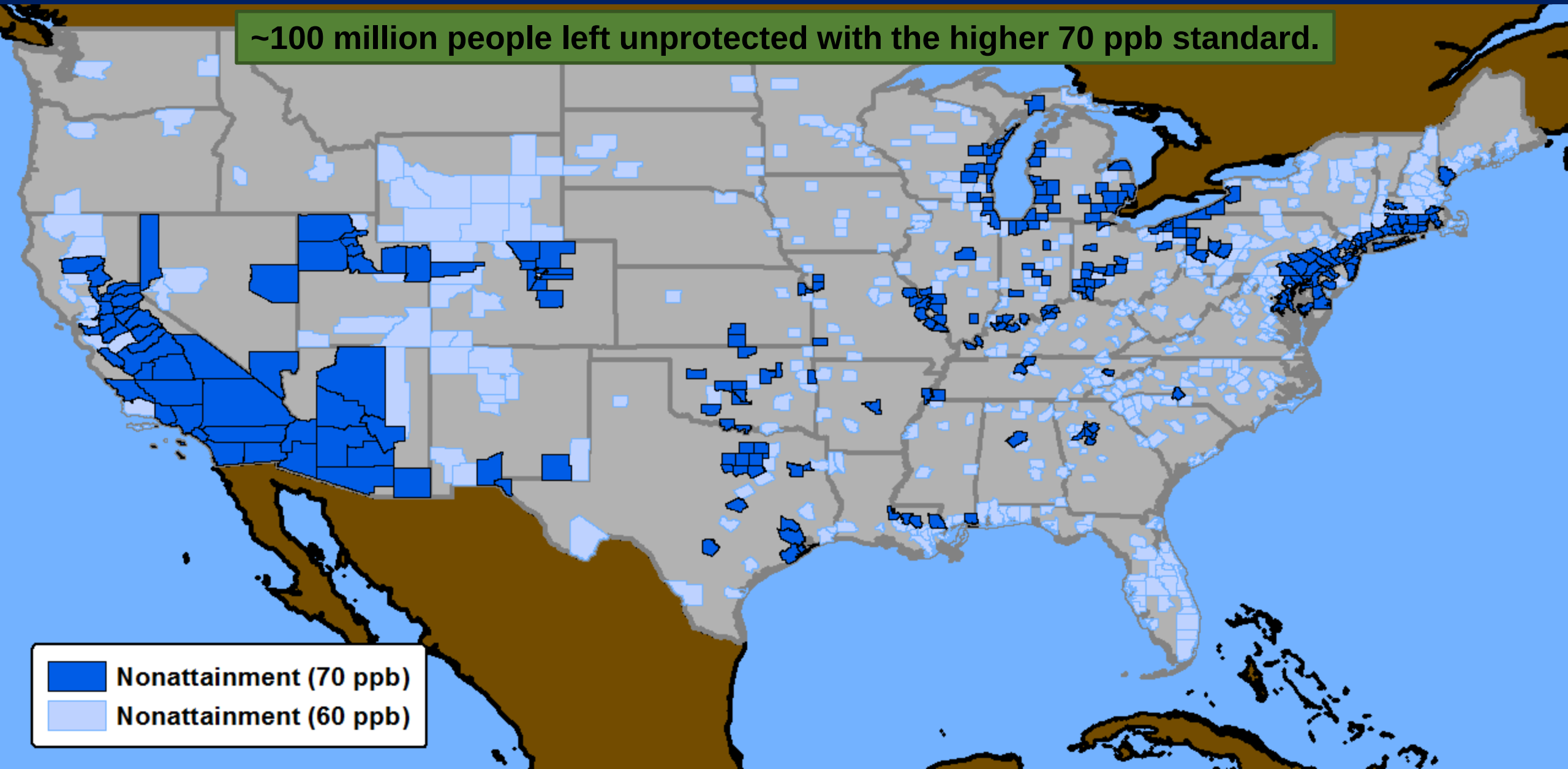
-Governor John Hickenlooper

Lawsuits pending by business and manufacturing groups, nine states, and environmental organizations.

Why Industry Groups are Unhappy



Why Environmental Groups are Unhappy



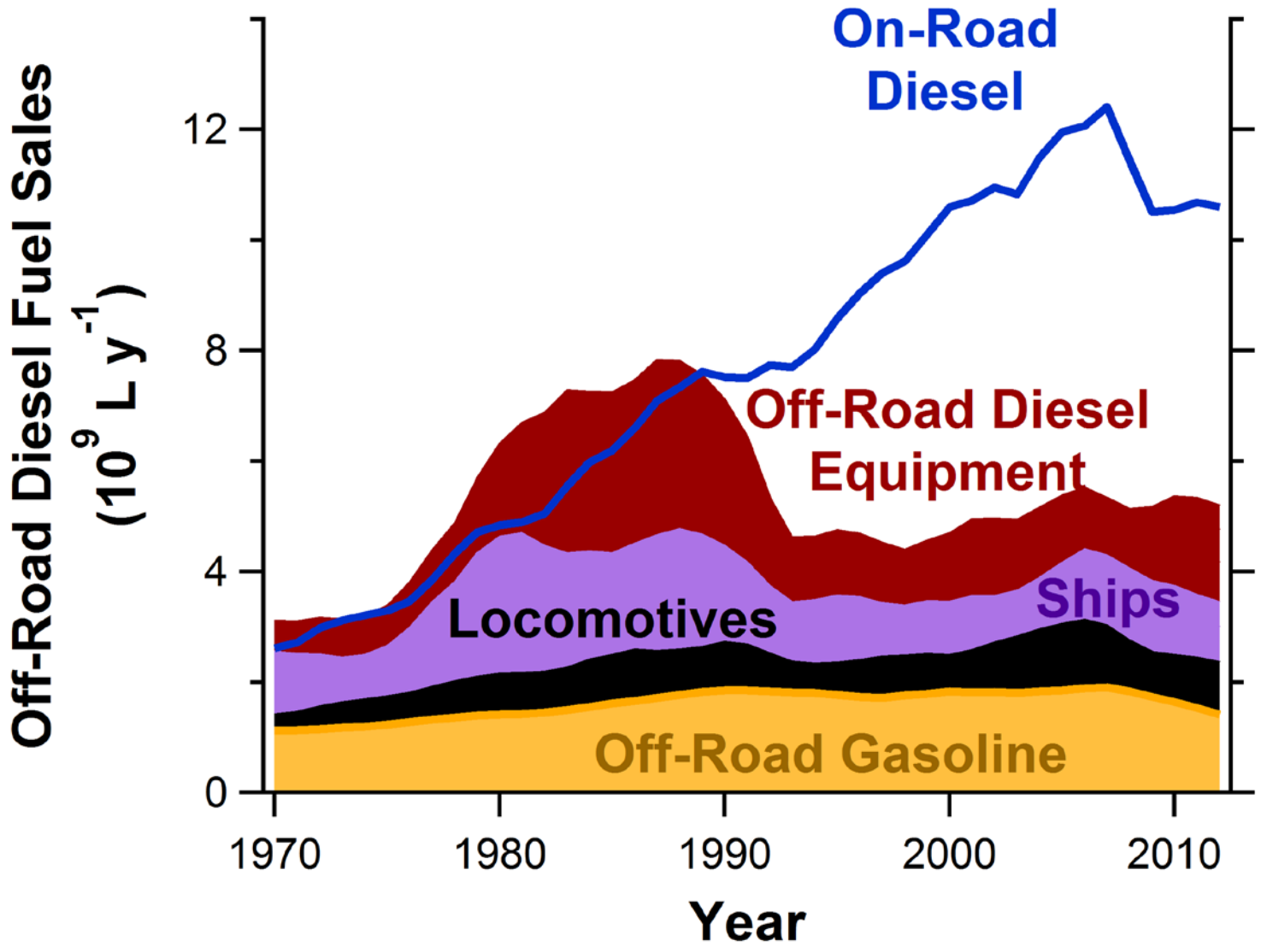
Summary of NO_x Emissions from Mobile Sources

- **On-road engines still an important source of NO_x emissions**
  - Account for ~2/3 of NO_x emissions in Los Angeles and ~1/3 of U.S. emissions

- **U.S. EPA tends to overestimate mobile source NO_x emissions**
  - …even though NO_x emissions are higher than expected from VW diesels
  - Impacts models of tropospheric O_3, especially over the Southeastern U.S.

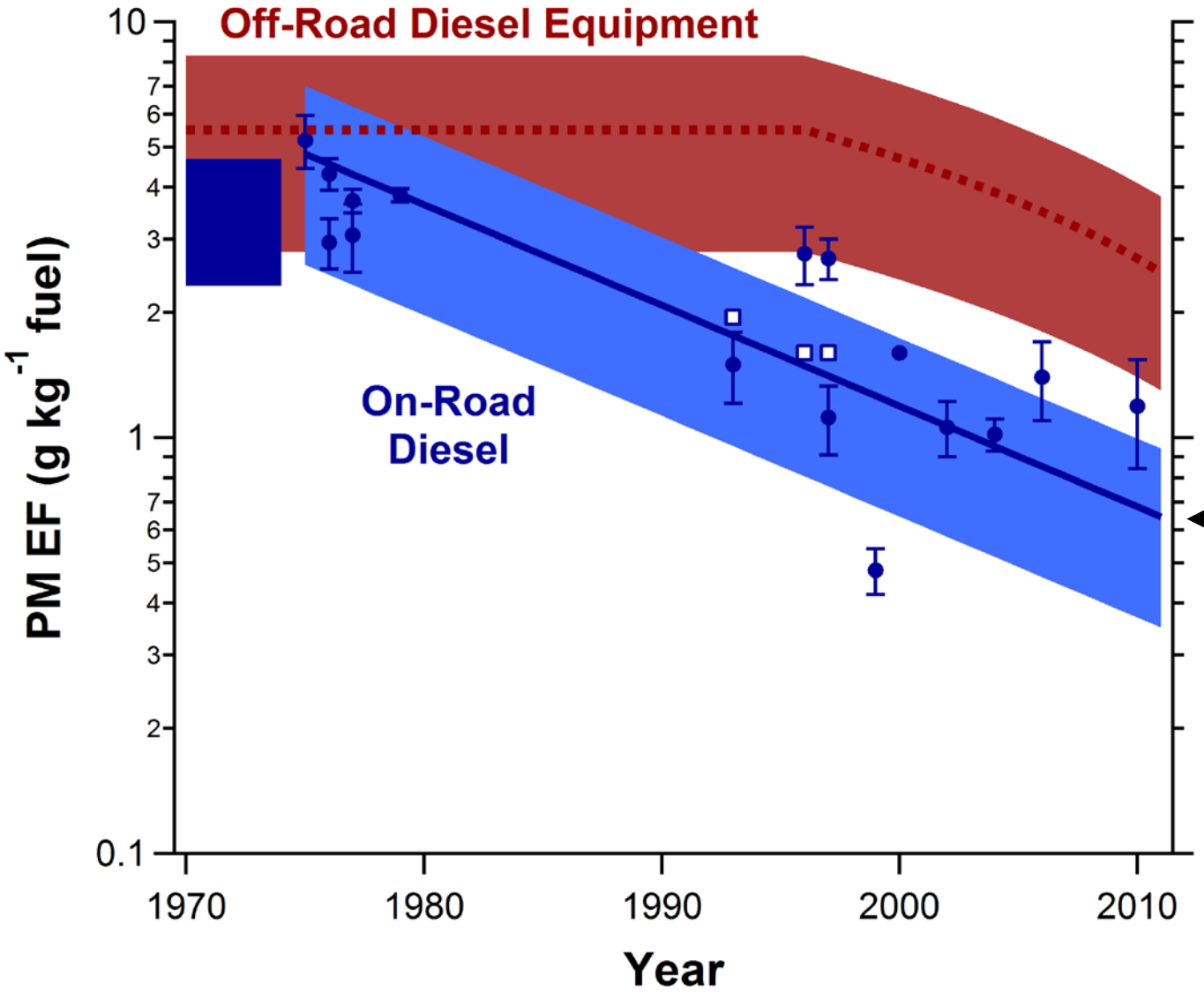
Emissions are a key input to atmospheric models, incumbent on the modeler to understand potential gaps in inventories used.

Trends in Diesel Fuel Use (California)



McDonald et al. (*Environ. Sci. & Technol.* 2015)

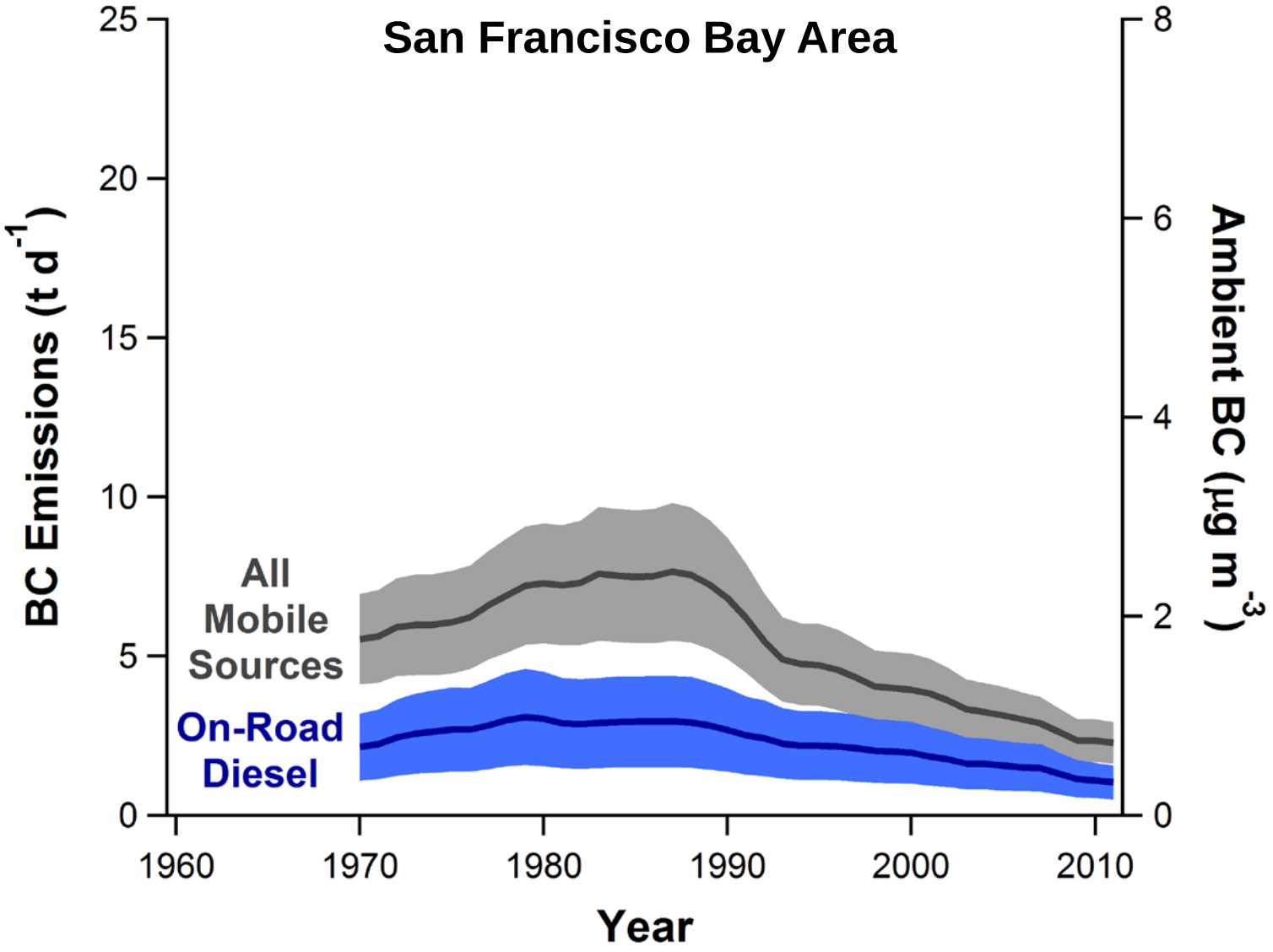
Trends in Diesel Engine PM Emission Factors



← Factor of ~6 reduction

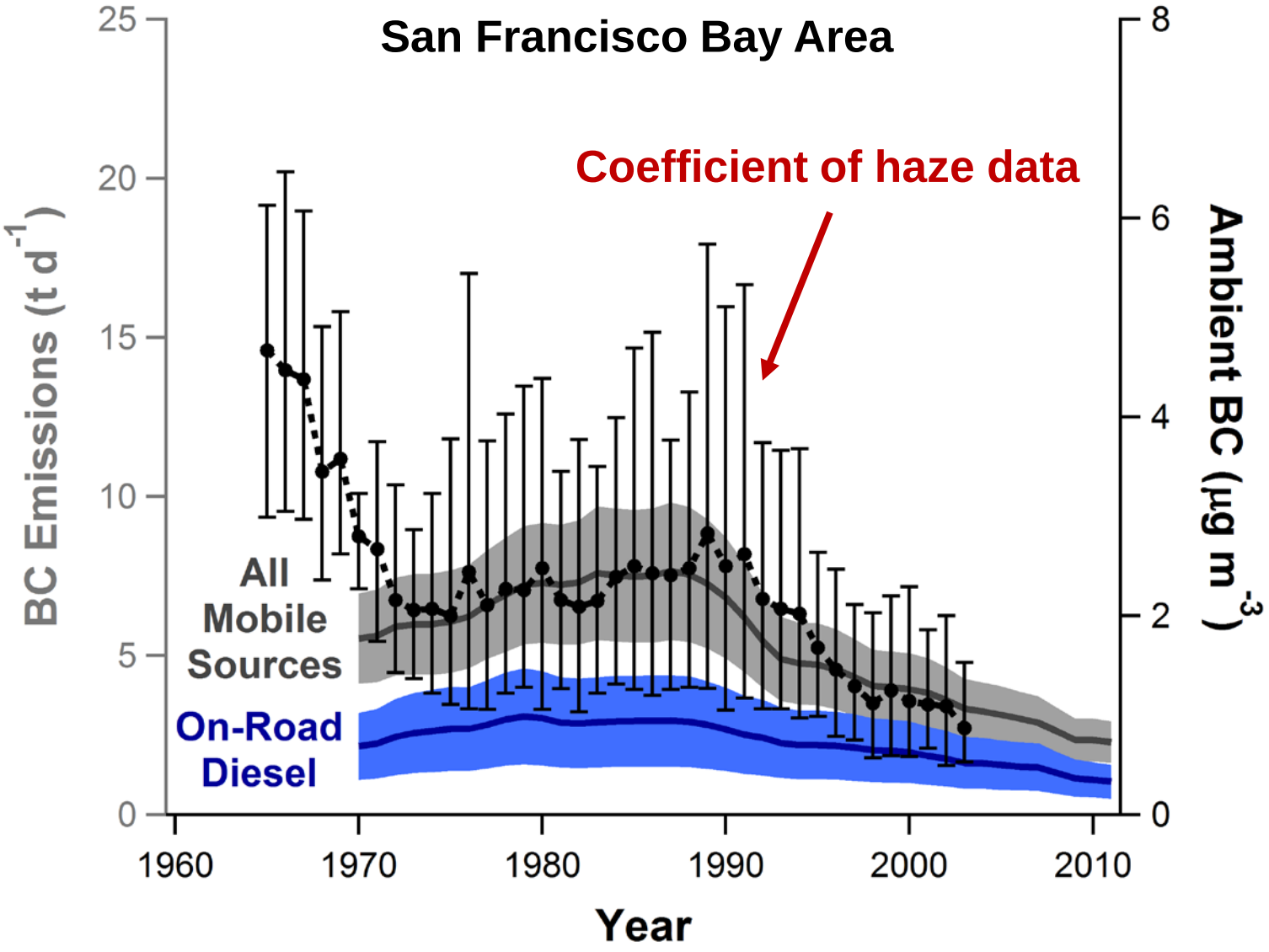
McDonald et al. (*Environ. Sci. & Technol.* 2015)

Trends in Mobile Source BC Emissions (California)



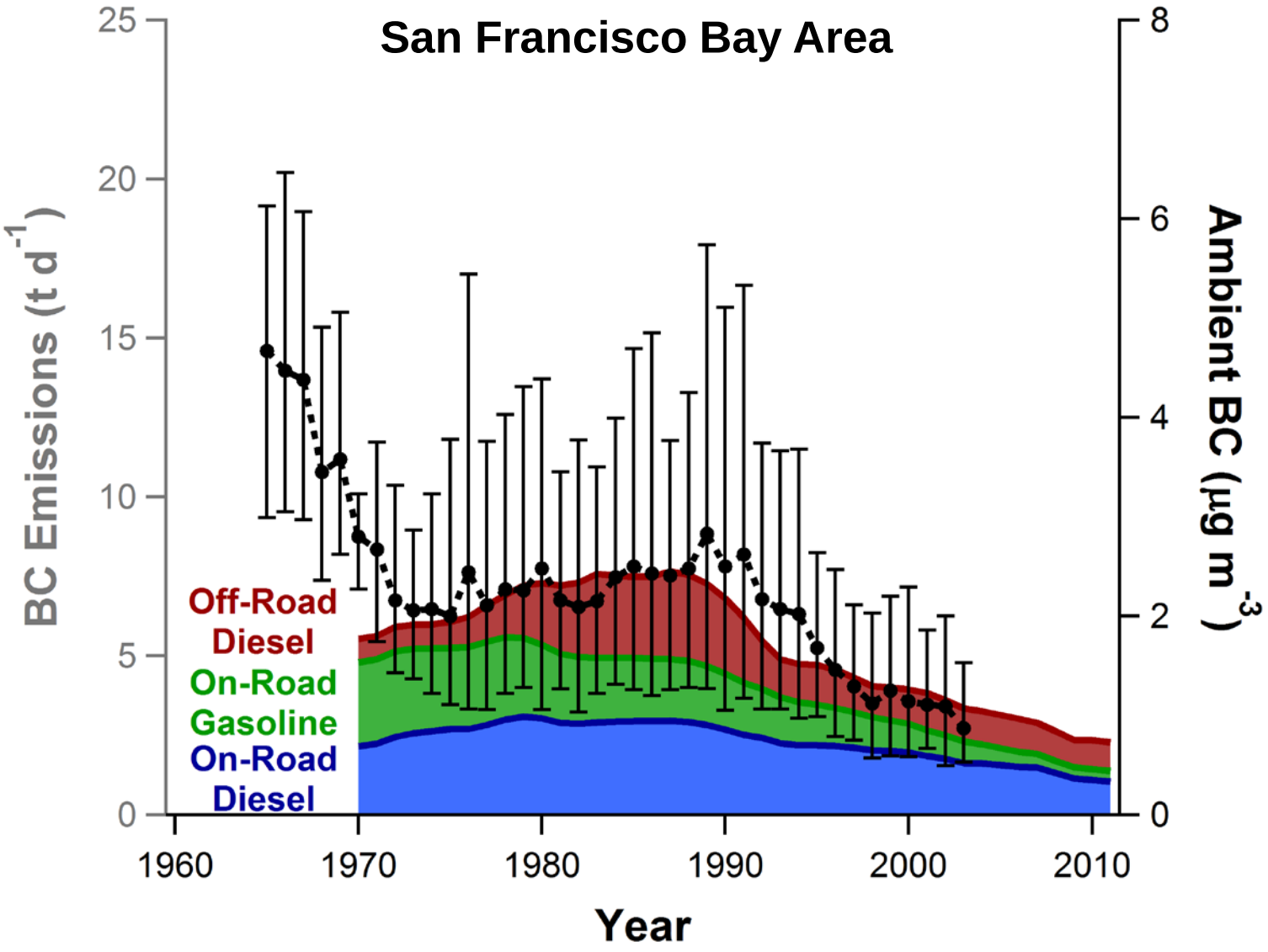
McDonald et al. (*Environ. Sci. & Technol.* 2015)

Consistency in Emissions and Ambient BC Trend



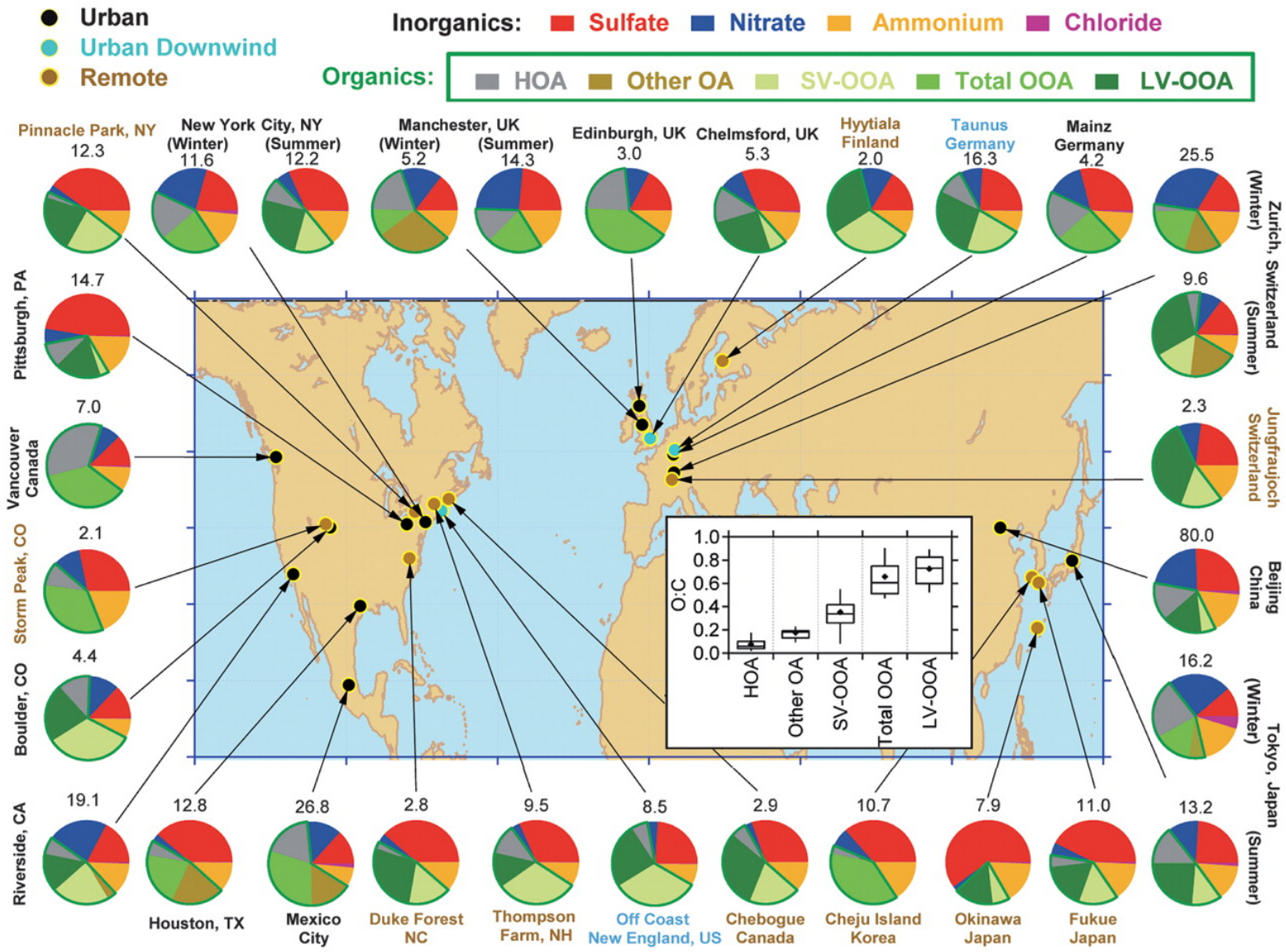
McDonald et al. (*Environ. Sci. & Technol.* 2015)

Composition of Mobile Source BC Shifted



McDonald et al. (*Environ. Sci. & Technol.* 2015)

Organic Aerosol a Major Fraction of Fine PM Around the World



Jimenez et al. (*Science* 2009)

Gasoline vs. Diesel Contribution to Organic Aerosol

Which mobile source sector dominates formation of SOA?

Los Angeles 2010

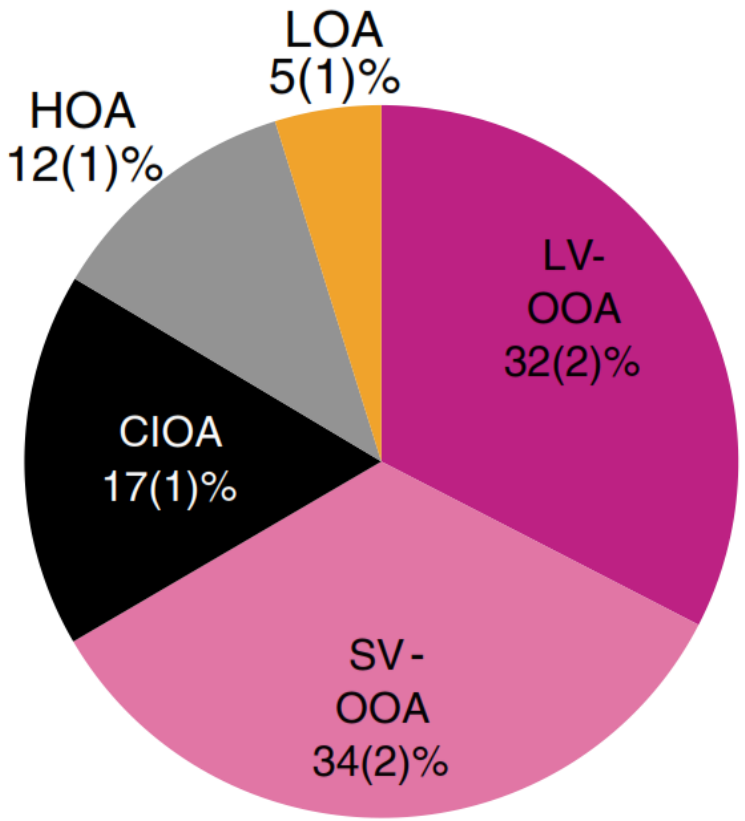
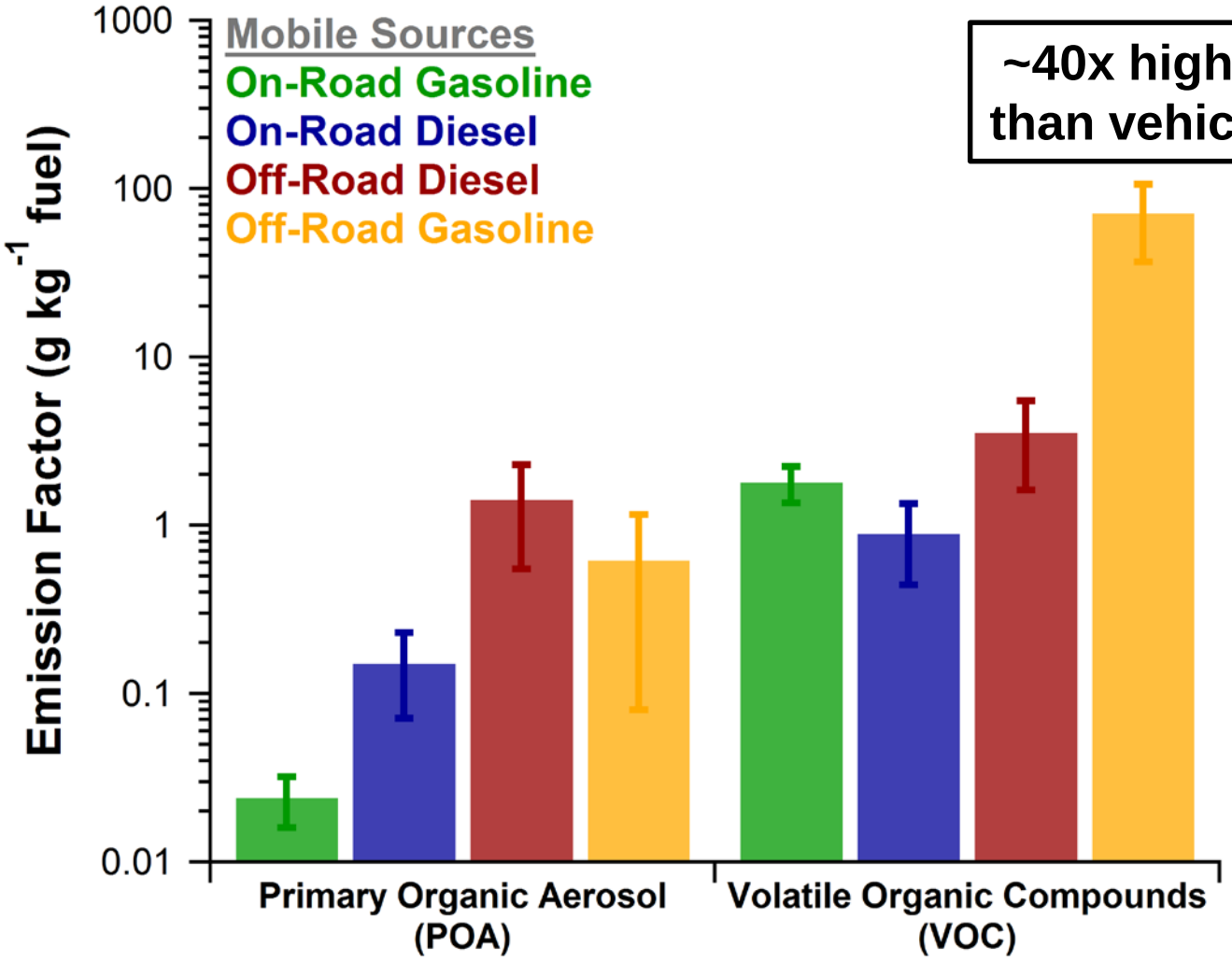


Figure from Hayes et al. (*J. Geophys. Res.* 2013)

- **Bahreini et al. (*GRL* 2012)**
  Concluded that gasoline emissions dominated anthropogenic SOA in LA
- **Gentner et al. (*PNAS* 2012)**
  Concluded that diesel emissions dominated anthropogenic SOA in LA
- **Platt et al. (*Nat Comm* 2014)**
  Found two-stroke scooters dominated mobile source SOA in many cities globally

Large Off-Road Engine Emission Factors

As of 2010



~40x higher than vehicle!

Figure from Burgard et al. (*Environ. Sci. & Technol.* 2011)

Emission factors from McDonald et al. (*Environ. Sci. & Technol.* 2015)

Trends in SOA Yields by Mobile Source Engine Type

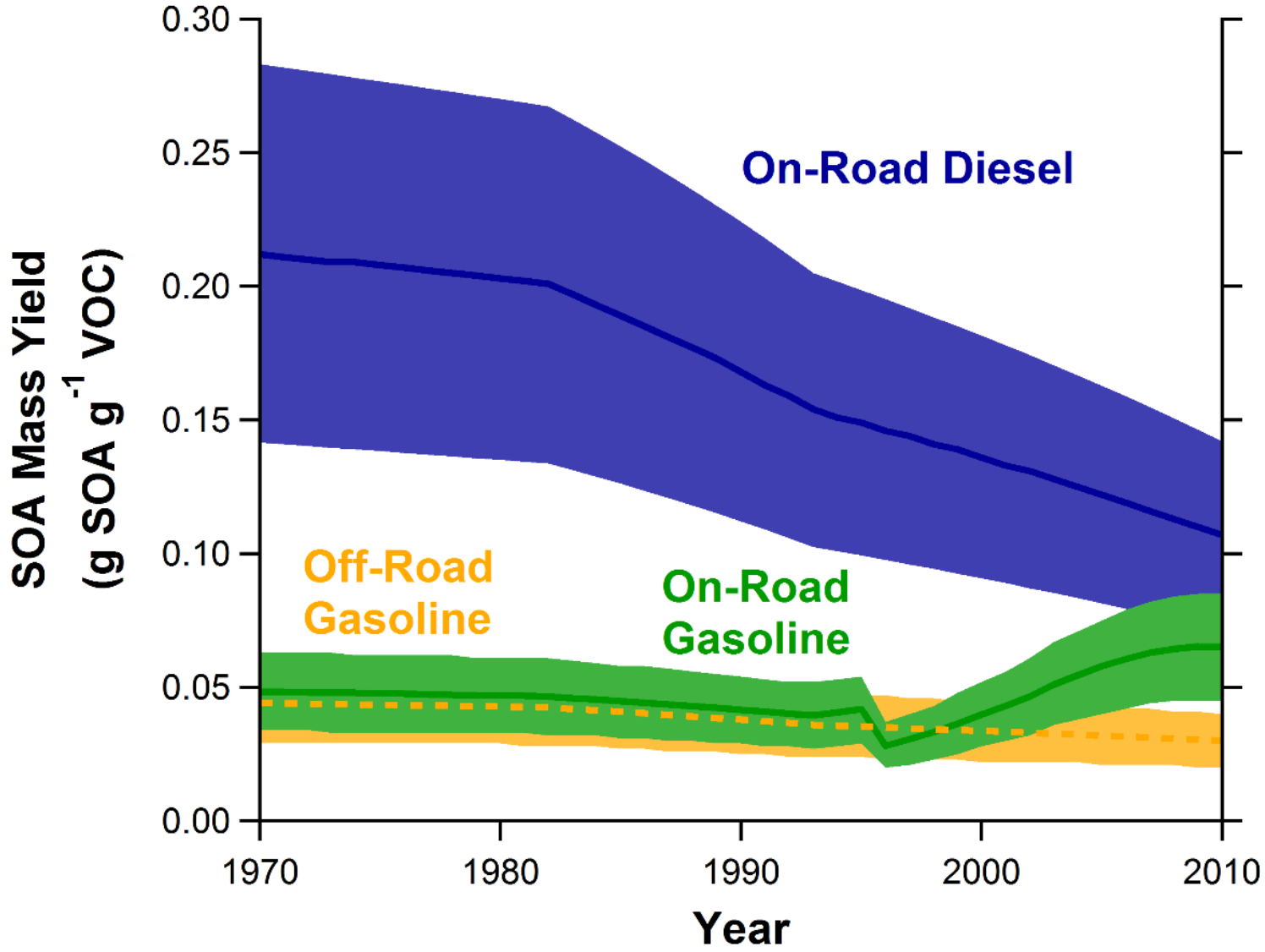
Factors that affect SOA yields

(1) Ambient OA mass loadings

(2) Exhaust VOC profiles (Gasoline vs. Diesel)

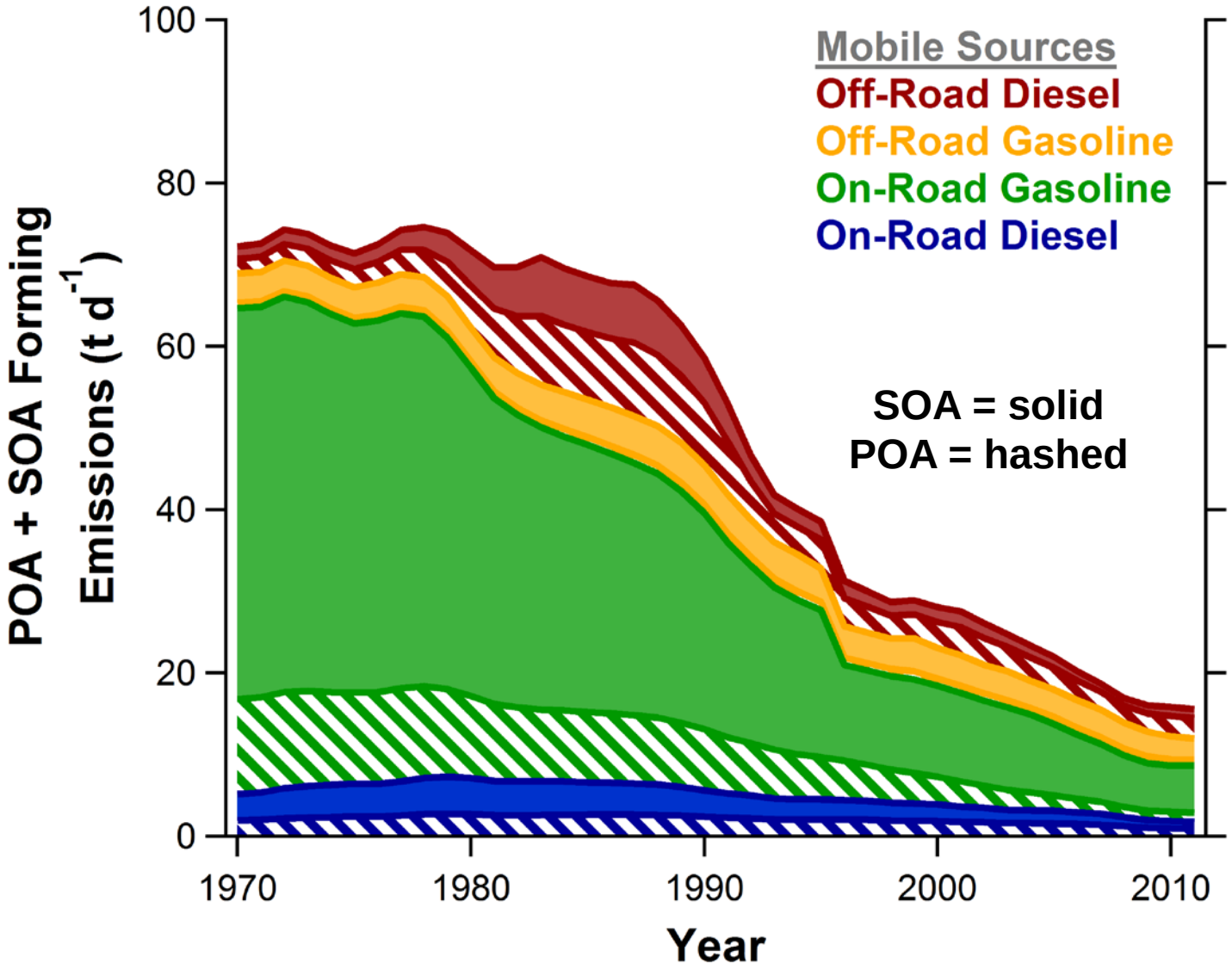
(3) Reformulated gasoline

(4) Higher aerosol yields in LEV-I and LEV-II vehicles



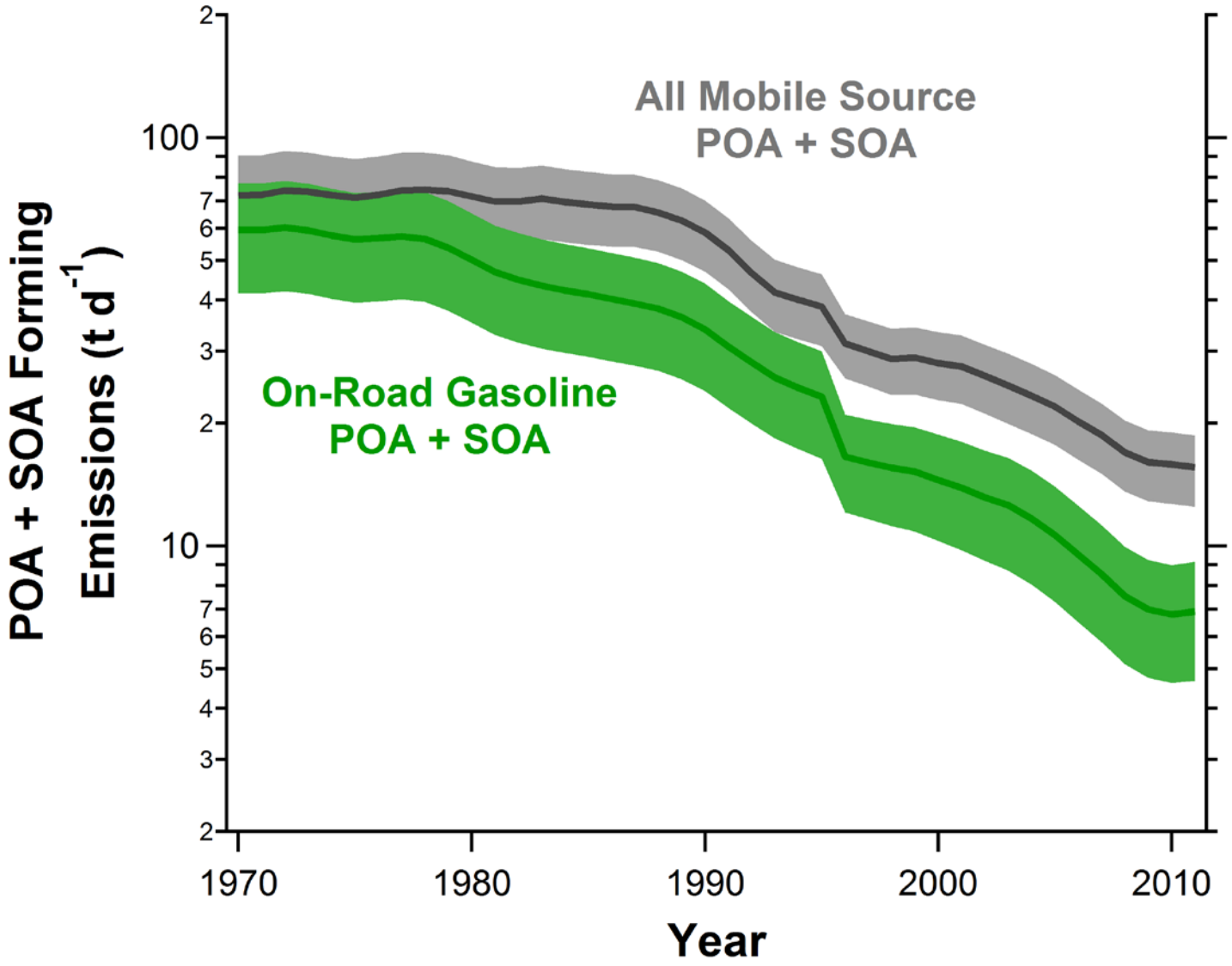
See McDonald et al. (*Environ. Sci. & Technol. 2015*) for more details.

Trend in Mobile Source OA (Los Angeles)



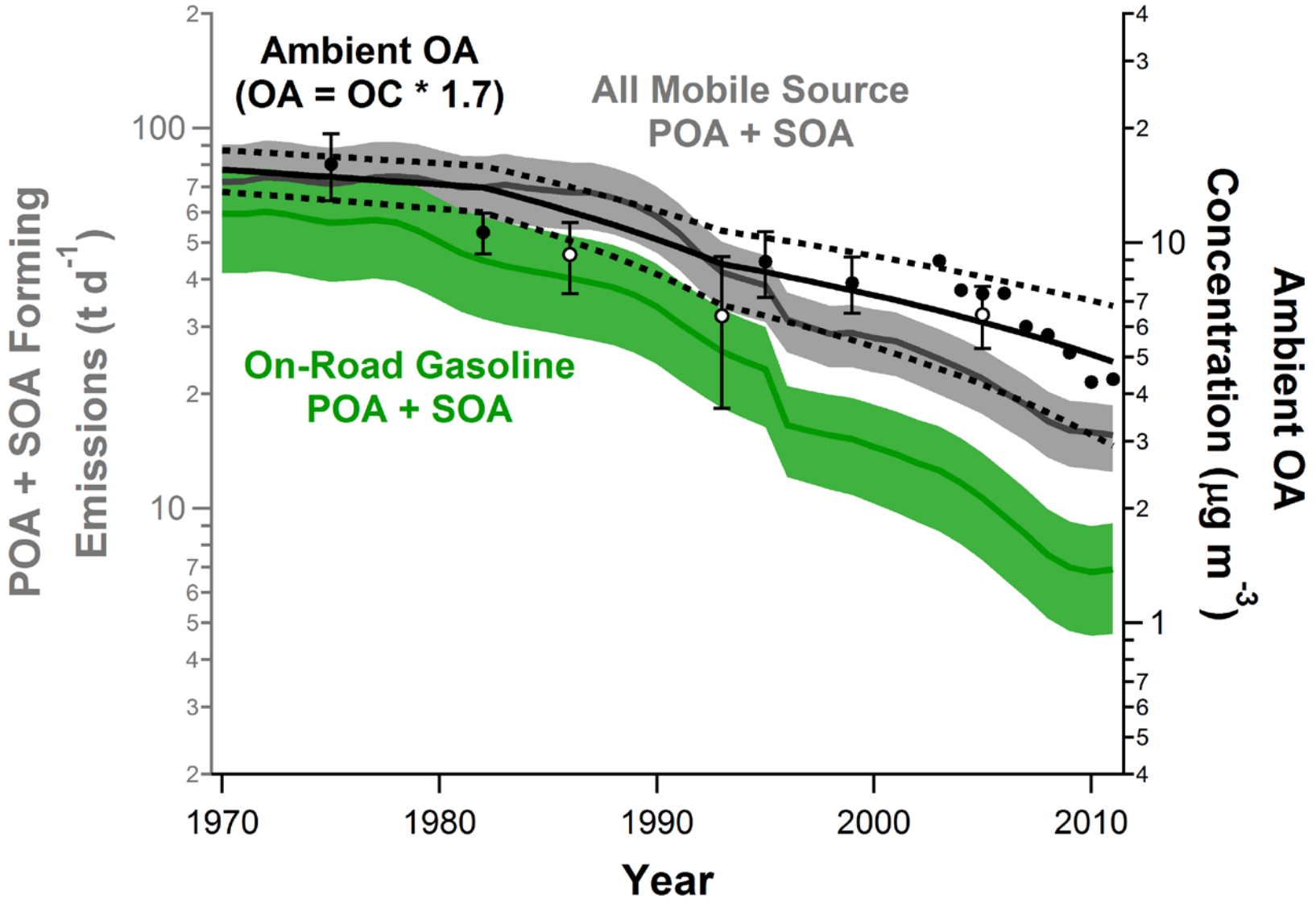
McDonald et al. (*Environ. Sci. & Technol. 2015*)

Adding Off-Road Engines Slow Emission Decreases



McDonald et al. (*Environ. Sci. & Technol. 2015*)

Consistency in Emissions and Ambient OA Trends



McDonald et al. (*Environ. Sci. & Technol. 2015*)

Summary of PM Emissions from Mobile Sources

- **Similar decreases in mobile source emissions and ambient trends of carbonaceous aerosols**
  - Suggests historical importance of mobile sources to urban concentrations of BC and OA

- **Growing relative contribution from non-vehicular sources**
  - Off-road engines now account for 40-50% of mobile source emissions of BC and OA in U.S.
  - Other VOC and POA sources (e.g. cooking, fires, solvents, etc.) likely important as well

Transportation is an important contributor to urban aerosol, but they are not the only emissions source of concern.

Case Study on Managing Air Quality and Climate Change

Are gasoline or diesel vehicles better for the environment?

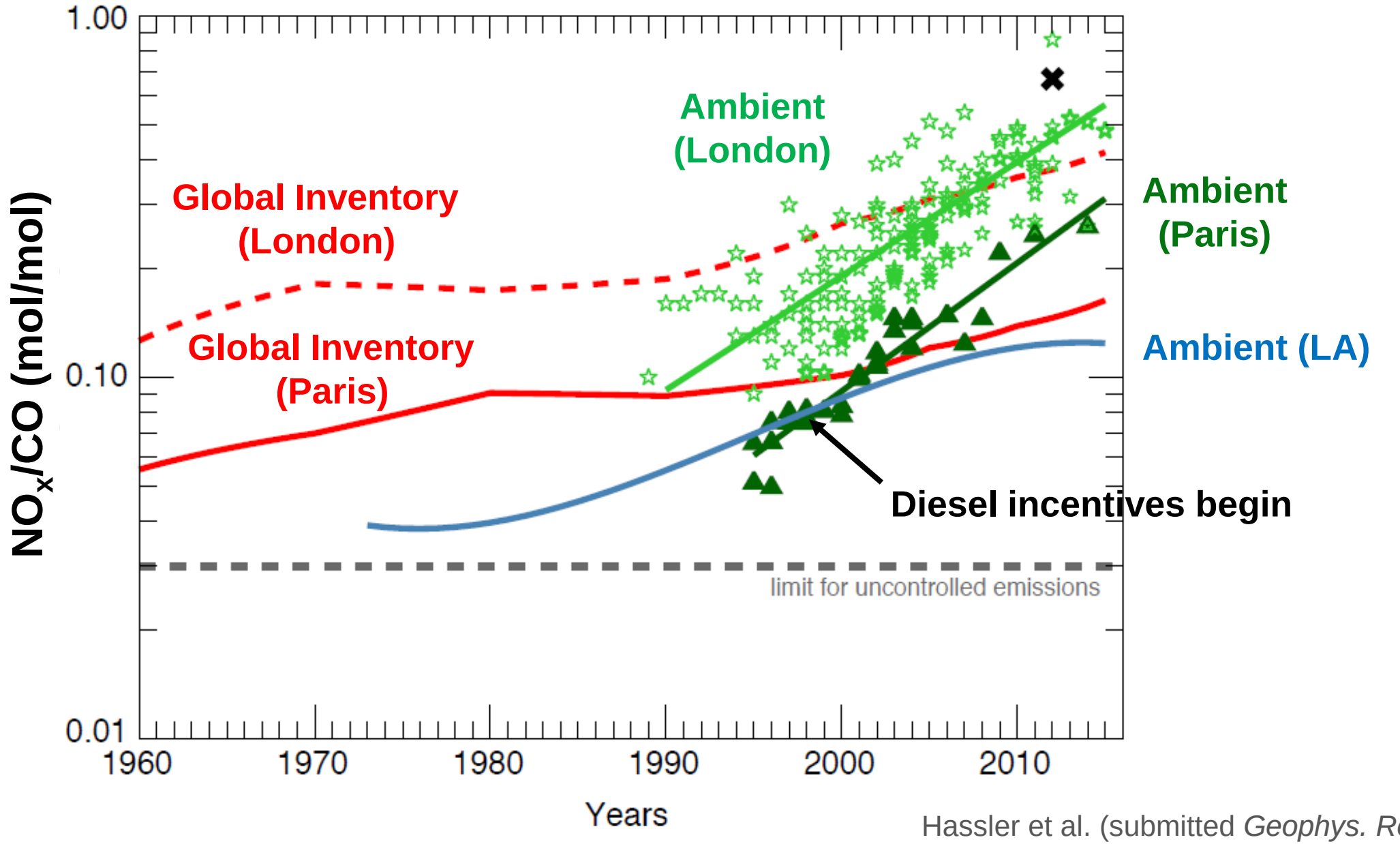
Automobiles mostly gasoline-powered

Emission control technologies more robust (e.g., three-way catalytic converters)

Automobiles ~50% diesel (varies by country)

Improved fuel efficiency by ~30%

Slower Decrease in Ambient NO_x in European Cities

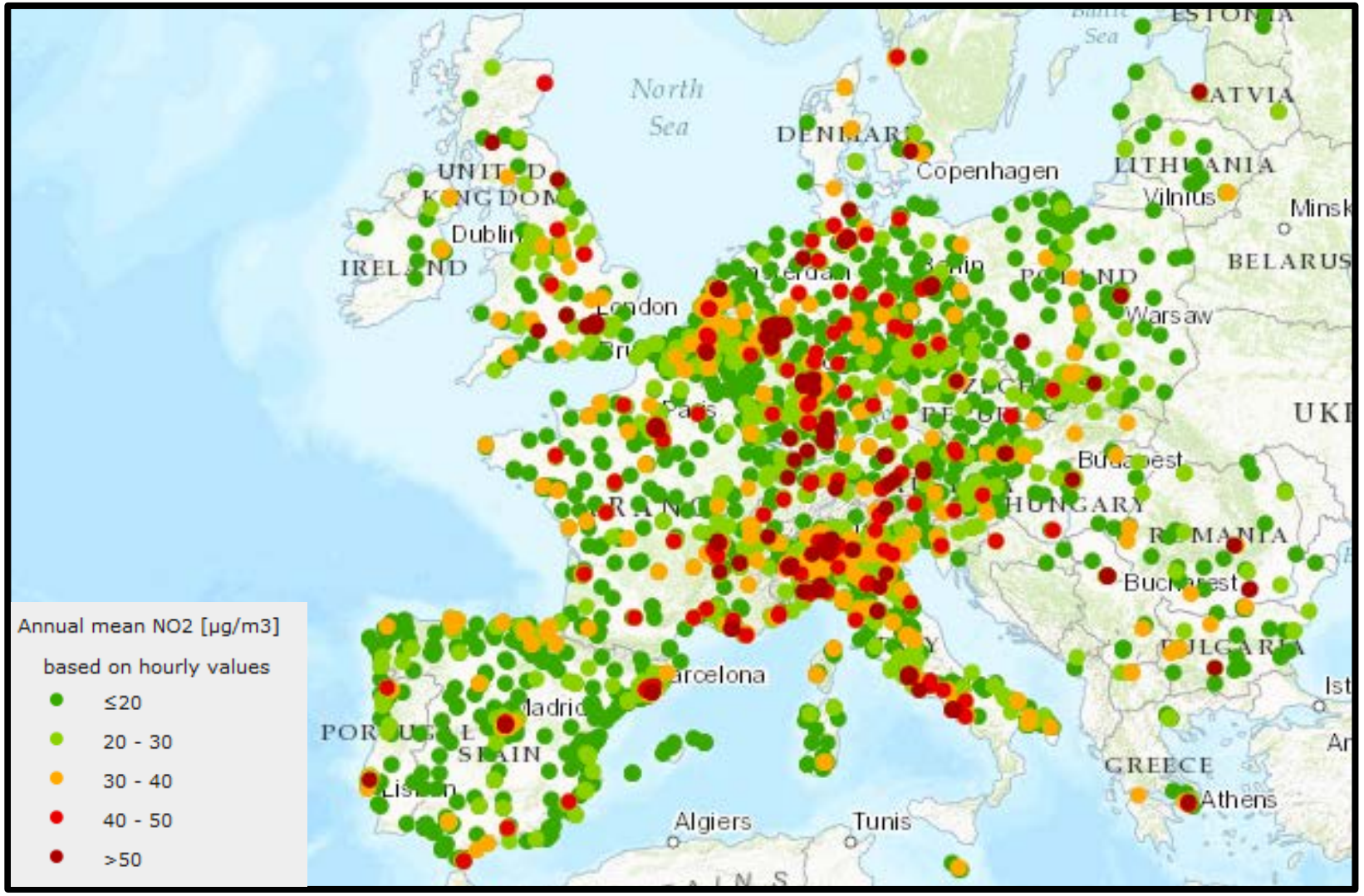


Hassler et al. (submitted *Geophys. Res. Let.*)

Congestion Pricing can also Lead to More Diesel Vehicles

£11.50 daily charge on weekdays between 7 AM and 6 PM

Annual NO_2 Concentrations across Europe



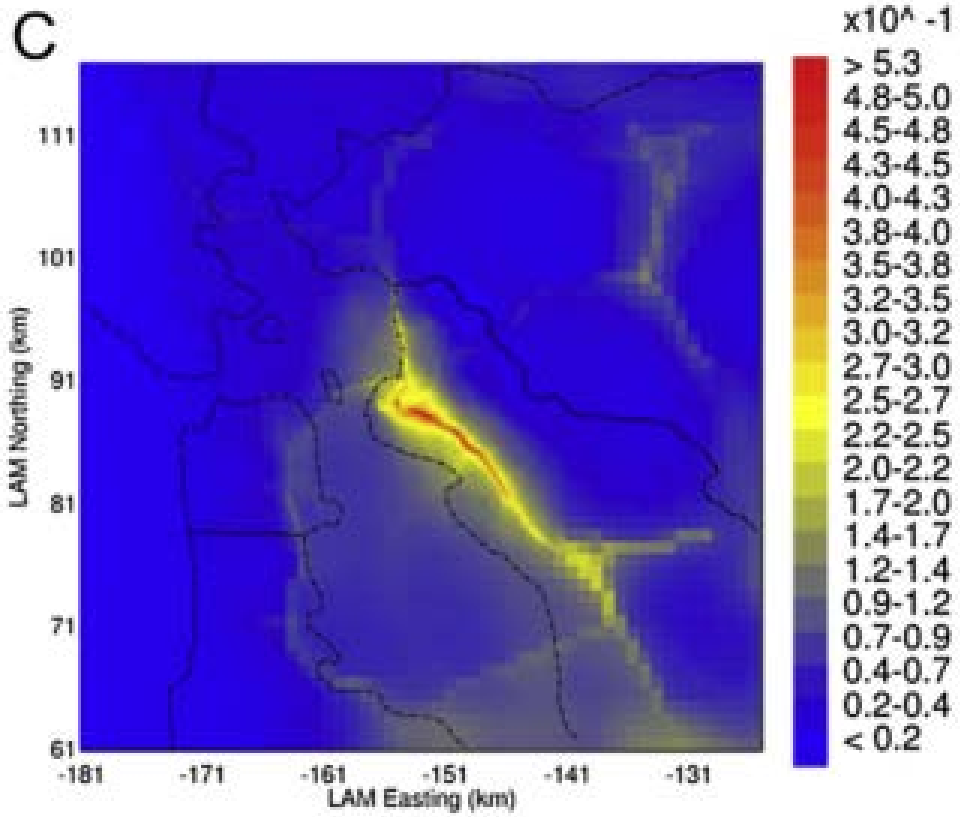
Many European cities violate ambient NO_2 standard (in red)

Source: European Environment Agency

What about the Impact of Diesel Emissions on Aerosols?

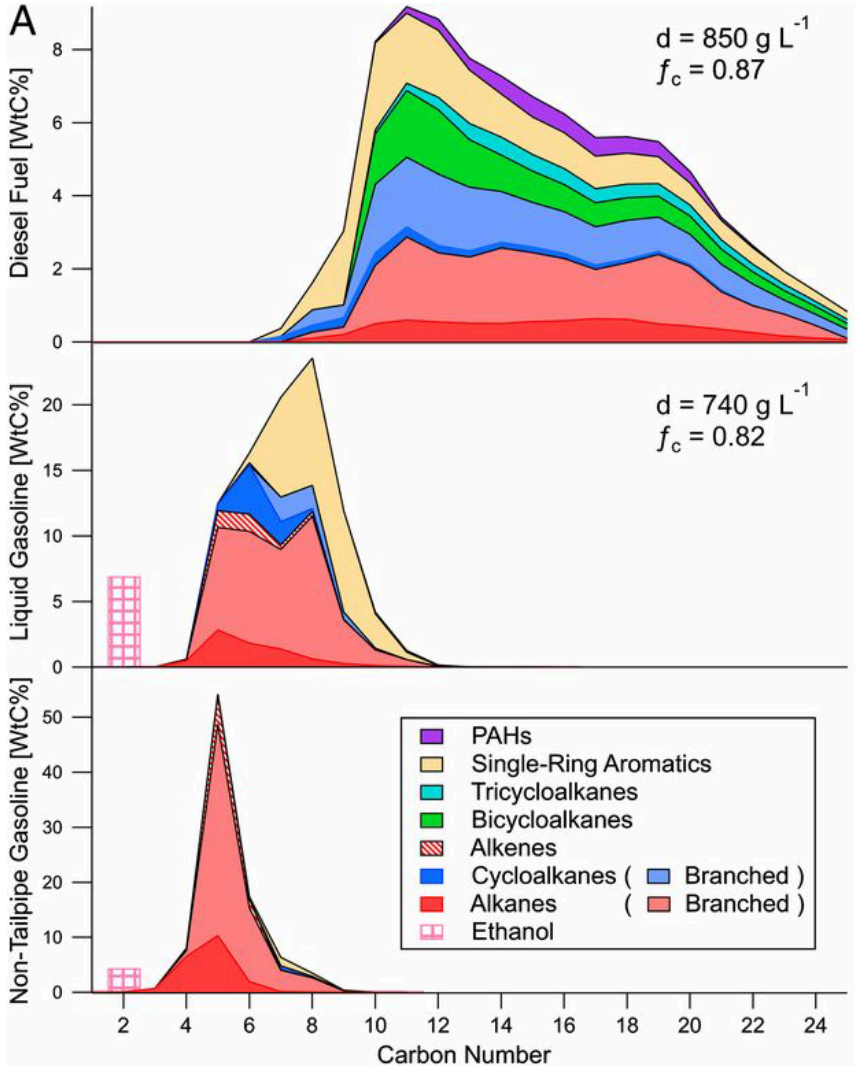
Near-Roadway Exposure to Primary Diesel Emissions

Port of Oakland, CA



BC Conc. µg m^{-3}

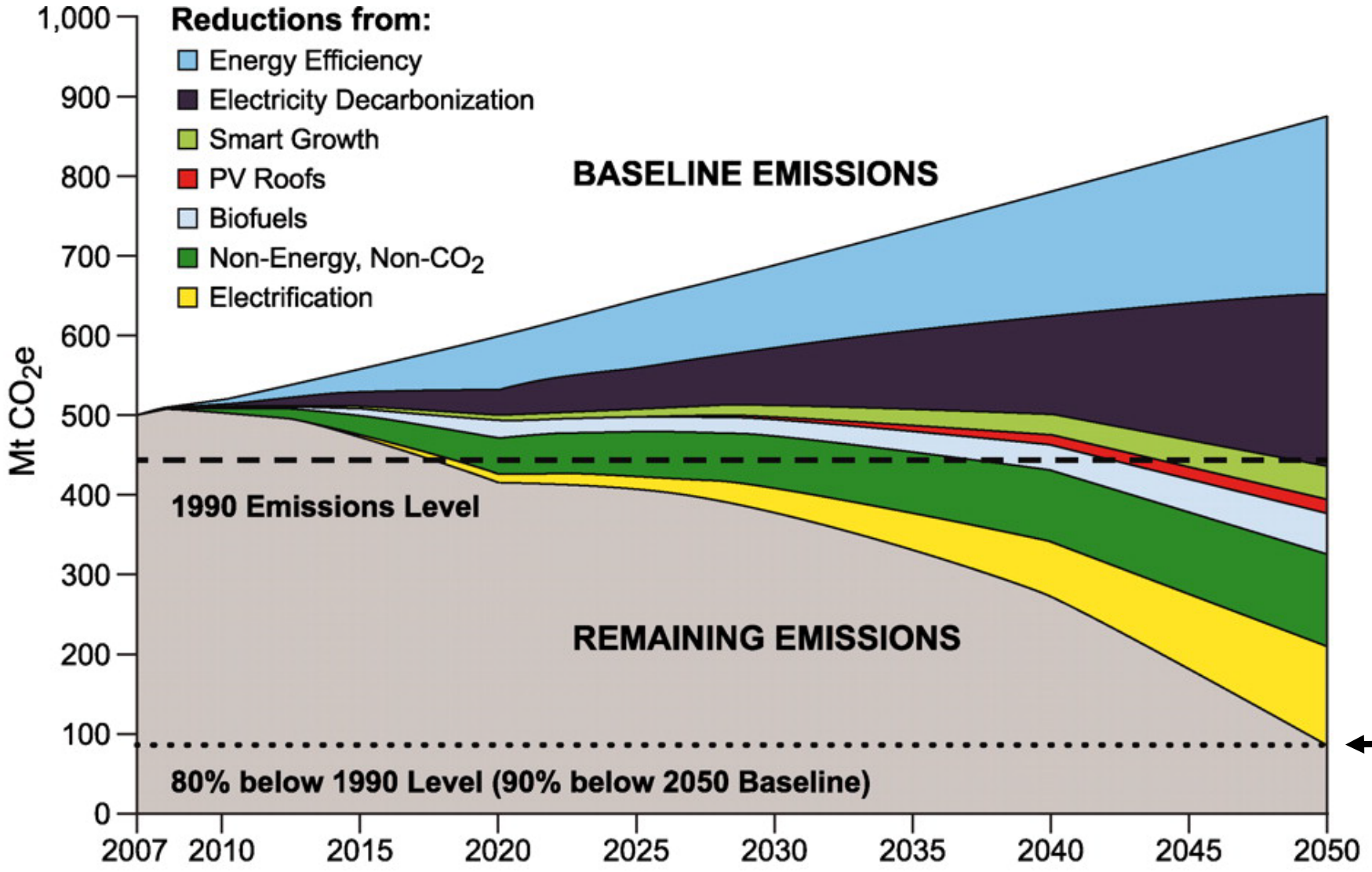
SOA Formation Potential



Joe et al. (*Atm. Env. 2014*)

Gentner et al. (*PNAS 2014*)

What is the Role of Electric Vehicles in Climate Mitigation?

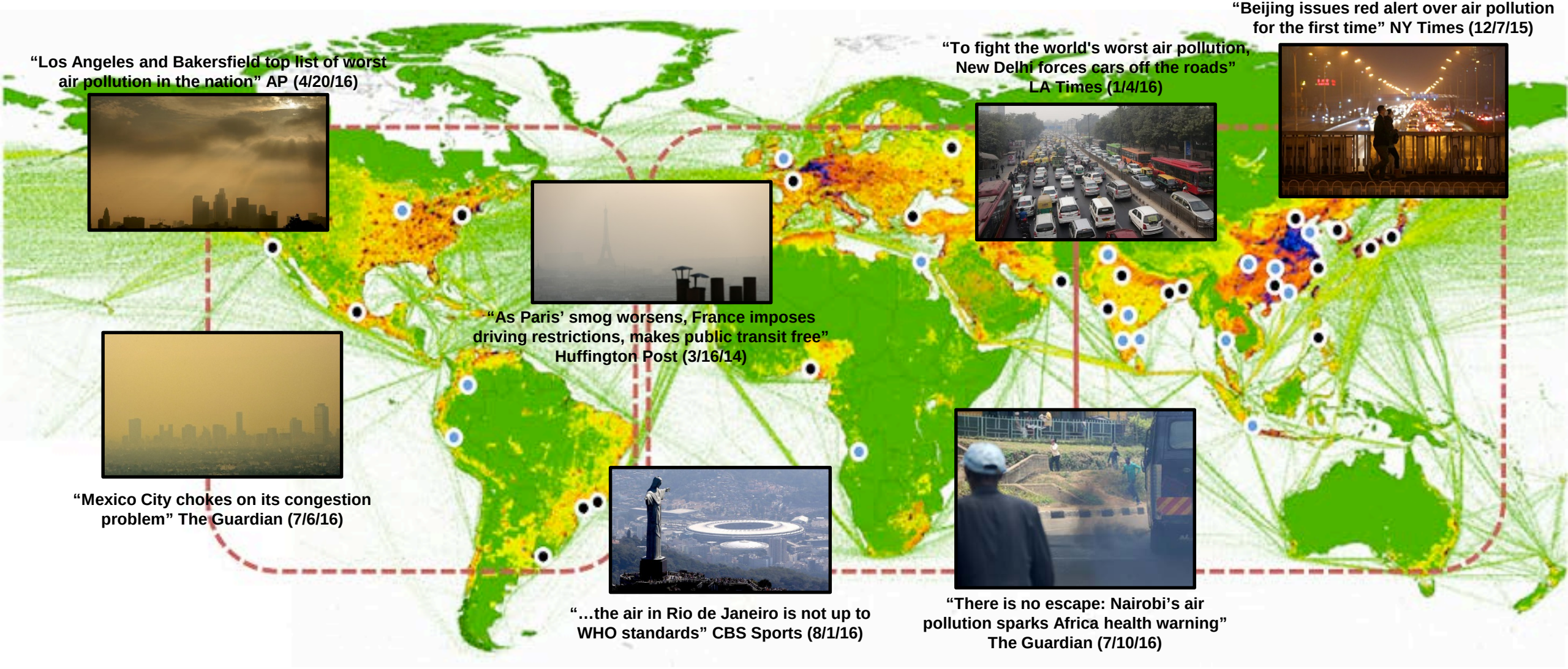


Energy efficiency, electricity de-carbonization, and vehicle electrification all needed

← Needed to stabilize CO_2e concentrations at 450 ppm

Williams et al. (*Science 2014*), The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: the Pivotal Role of Electricity

Cities account for ~70% of global fossil fuel CO_2 emissions
Clean transportation key to mitigating poor air quality and climate change



"Los Angeles and Bakersfield top list of worst air pollution in the nation" AP (4/20/16)

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Background CO_2 emissions map from NASA JPL, Megacities Carbon Project

Acknowledgments

NOAA Chemical Sciences Division

(Regional Chemical Modeling, Tropospheric Chemistry, Chemistry & Climate Processes)

Si-Wan Kim, Stuart McKeen, Ravan Ahmadov, Yuyan Cui, Greg Frost, Michael Trainer, Joost de Gouw, Birgit Hassler

University of Denver

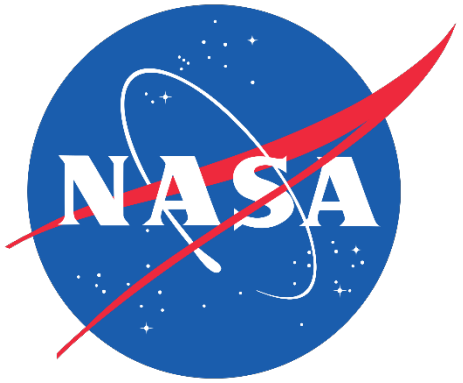
Gary Bishop and Don Stedman

UC-Berkeley

Rob Harley and Allen Goldstein

University of York

David Carslaw



Key Takeaways

- **Mobile sources still contribute to urban air quality problems**
  - Policy-relevant impacts on tropospheric O_3
  - Primary and secondary emissions of fine particles
  - U.S. successful at controlling criteria air pollutants, but not CO_2
  - Contrasting air quality trends with Europe

- **What is the pathway forward for sustainable transportation systems?**
  - Gasoline vs. diesel vs. electric vehicles?
  - Answer highly intertwined with energy infrastructure
  - May vary by different regions of the world

A holistic view is required that considers both air quality and climate change.