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\textsubscript{x} Emission Factors

![Graph showing NO\textsubscript{x}/CO\textsubscript{2} volume ratio from 1980 to 2010 for Diesel and Gasoline vehicles. The graph shows a trend of improvement for Diesel vehicles and worsening for Gasoline vehicles.](image)

Carslaw et al. (Atm. Env. 2011)
U.S. Trends in Diesel Vehicle NO$_x$ Emission Factors

![Graph showing NO$_x$ emissions from diesel vehicles over time]

- New Car ~0.4 g/kg fuel
- Real-world vehicle fleet

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 they emit?

(2) What is the impact of nitrogen oxide ($\text{NO}_x$) emissions on ozone ($\text{O}_3$)?

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

(4) What is the pathway forward for sustainable transportation systems?
Mobile Sources are a major source of GHGs and air toxics

- ~70% CO
- ~30% CO₂
- ~50% Nitrogen Oxides
- ~50% Black Carbon

In US...

- ~230 million cars + ~3 million freight trucks
- ~600 coal-fired power plants
- ~1700 natural-gas plants

Challenge to estimate emissions
- Scale and mobility
- Not continuously monitored
- Vehicles evolving
## Key Features of Gasoline and Diesel Engines

<table>
<thead>
<tr>
<th>Gasoline Engine</th>
<th>Diesel Engine</th>
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<tbody>
<tr>
<td><strong>Spark ignition</strong>&lt;br&gt;(octane: rated to avoid premature ignition)</td>
<td><strong>Compression ignition</strong>&lt;br&gt;(cetane: rated for ease of ignition)</td>
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<tr>
<td>Fuel comprised of aromatics, branched-alkanes</td>
<td>Fuel comprised of long-chain n-alkanes</td>
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<td>Stoichiometric combustion, air-fuel <strong>pre-mixed</strong></td>
<td>Fuel lean combustion, air-fuel <strong>not pre-mixed</strong></td>
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<td>Pollutants of concern: CO, VOCs, NO$_x$</td>
<td>Pollutants of concern: NO$_x$, PM, aldehydes</td>
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<td>Common Vehicle Emission Control Technologies</td>
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<td>---------------------------------------------</td>
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<tr>
<td><strong>Gasoline Engine</strong></td>
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<tr>
<td>Three-way catalytic converters</td>
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<tr>
<td>Oxidation of CO, VOCs → CO₂</td>
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<tr>
<td>Reduction of NOₓ → N₂</td>
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<tr>
<td>Positive crankcase ventilation</td>
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<td>Control evaporative VOC emissions</td>
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<tr>
<td><strong>Diesel Engine</strong></td>
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<tr>
<td>Selective catalytic reduction systems</td>
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<tr>
<td>Reduction of NOₓ → N₂ using urea</td>
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<tr>
<td>or NOₓ lean trap</td>
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<tr>
<td>NOₓ removed by adsorption, requires <strong>regeneration</strong></td>
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<tr>
<td>Diesel oxidation catalyst</td>
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<td>Diesel particle filters</td>
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<td>Traps PM, requires <strong>regeneration</strong></td>
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</table>
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)
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

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 CO₂ emissions**
- State-level taxable gasoline and diesel fuel sales reports
- Public and annual

**Map on-road CO₂ 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
Long-Term Trends in U.S. On-Road NO$_x$ Emission Factors

Diesel engines emit high amounts of NO$_x$.

Three-way catalytic converters effective.

HD Defeat Devices

Heavy-Duty (Diesel)

Light-Duty (Gasoline)

Figure updated from McDonald et al. (J. Geophys. Res. 2012)
Comparison with Current EPA Vehicle Emissions Model (MOVES)

Gasoline EF high by factor of ~2

Diesel EF within ~20%

MOVES2014

Light-Duty (Gasoline)

Heavy-Duty (Diesel)

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)
Strong Agreement between Model and Aircraft Observations

WRF-Chem Model

NOAA P-3 Aircraft

Kim et al. (J. Geophys. Res. 2016)
Difference in Total U.S. NO$_x$ Emissions (Fuel-Based – EPA)

2013: ΔUrban NO$_x$ ~ -20%  ΔRural NO$_x$ ~ -10%

Problems in light-duty vehicle emissions enough to bias whole U.S. NO$_x$ inventory.
Comparisons windowed to boundary layer (200-700 m) and daytime (10 AM-6 PM CDT)

**NO\textsubscript{y}** error (ppb\textsubscript{v})
- Obs. median = 2.0 ppb\textsubscript{v}
- NEI 2011: (n = 12158, r = 0.53)
- FIVE: (n = 12158, r = 0.53)

**O\textsubscript{3}** error (ppb\textsubscript{v})
- Obs. median = 50 ppb\textsubscript{v}
- NEI 2011: (n = 12615, r = 0.83)
- FIVE: (n = 12615, r = 0.80)

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 NOx emissions
  e.g. oil & gas, agriculture

Overall improvement in ozone prediction

Gray dots within 5 ppb of observations

△O₃ Bias (ppb)

+4  +2  0  -2  -4

Improved

McDonald et al. (in preparation)
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.”

“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

Number of counties violating ozone standard increased from ~70 to ~250 counties.
Why Environmental Groups are Unhappy

~100 million people left unprotected with the higher 70 ppb standard.
On-road engines still an important source of NO\textsubscript{x} emissions
• Account for ~2/3 of NO\textsubscript{x} emissions in Los Angeles and ~1/3 of U.S. emissions

U.S. EPA tends to overestimate mobile source NO\textsubscript{x} emissions
• …even though NO\textsubscript{x} emissions are higher than expected from VW diesels
• Impacts models of tropospheric O\textsubscript{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

San Francisco Bay Area

Coefficient of haze data

BC Emissions (t d⁻¹)

Ambient BC (µg m⁻³)

Year


All Mobile Sources
On-Road Diesel

McDonald et al. (Environ. Sci. & Technol. 2015)
Composition of Mobile Source BC Shifted

San Francisco Bay Area

BC Emissions ($\text{t d}^{-1}$)

Ambient BC ($\mu\text{g m}^{-3}$)

Year


Off-Road Diesel
On-Road Gasoline
On-Road Diesel

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

Los Angeles 2010

- **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

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

POA + SOA Forming Emissions (t d⁻¹)

Mobile Sources
- Off-Road Diesel
- Off-Road Gasoline
- On-Road Gasoline
- On-Road Diesel

SOA = solid
POA = hashed

McDonald et al. (Environ. Sci. & Technol. 2015)
Adding Off-Road Engines Slow Emission Decreases

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.
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\textsubscript{x} in European Cities

Diesel incentives begin

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 NO₂ Concentrations across Europe

Many European cities violate ambient NO₂ 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. \( \mu g \text{ m}^{-3} \)

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 CO₂e 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 CO₂ 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)

“Mexico City chokes on its congestion problem” The Guardian (7/6/16)

“As Paris’ smog worsens, France imposes driving restrictions, makes public transit free” Huffington Post (3/16/14)

“...the air in Rio de Janeiro is not up to WHO standards” CBS Sports (8/1/16)

“To fight the world’s worst air pollution, New Delhi forces cars off the roads” LA Times (1/4/16)

“Beijing issues red alert over air pollution for the first time” NY Times (12/7/15)

“There is no escape: Nairobi’s air pollution sparks Africa health warning” The Guardian (7/10/16)
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UC-Berkeley
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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.