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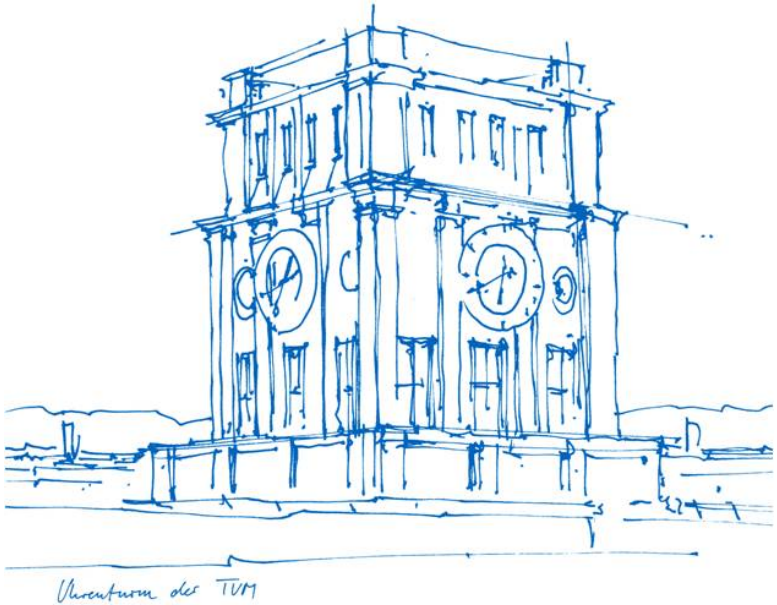
New Method of Diesel Particulate Matter Estimation with NO_X to BC Correlation

Master's Thesis | Umweltingenieurwesen
Munich, 23 Oktober 2017



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Technische Universität München
Supervisors: **Prof. Dr.- Ing. Jia Chen**
Professur für Umweltsensorik und Modellierung
Prof. Dr. Annette Menzel
Professur für Ökoklimatologie

Done in cooperation with the **South Coast Air Quality Management District**

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Overview

1. Background
2. DPM Estimation Methods
3. Combined Alpha Method of estimating DPM
4. NO_X to BC Correlation at three geographically different locations
5. Conclusion

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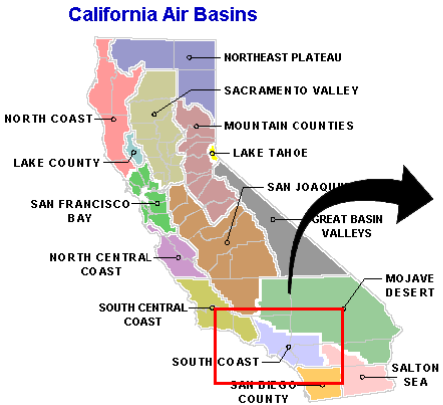
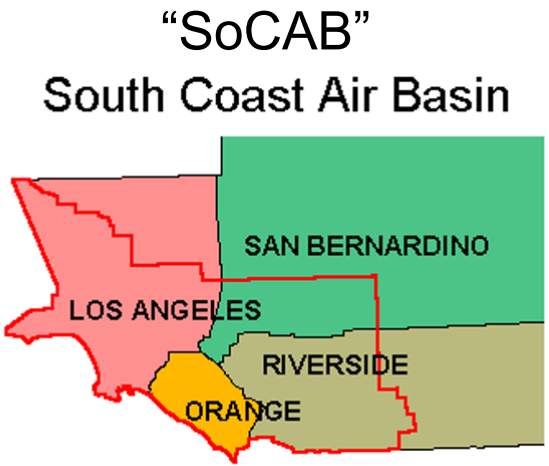
Background

Done in cooperation with:

South Coast Air Quality Management District (SCAQMD)
21865 Copley Drive, Diamond Bar, CA 91765
http://aqmd.gov/





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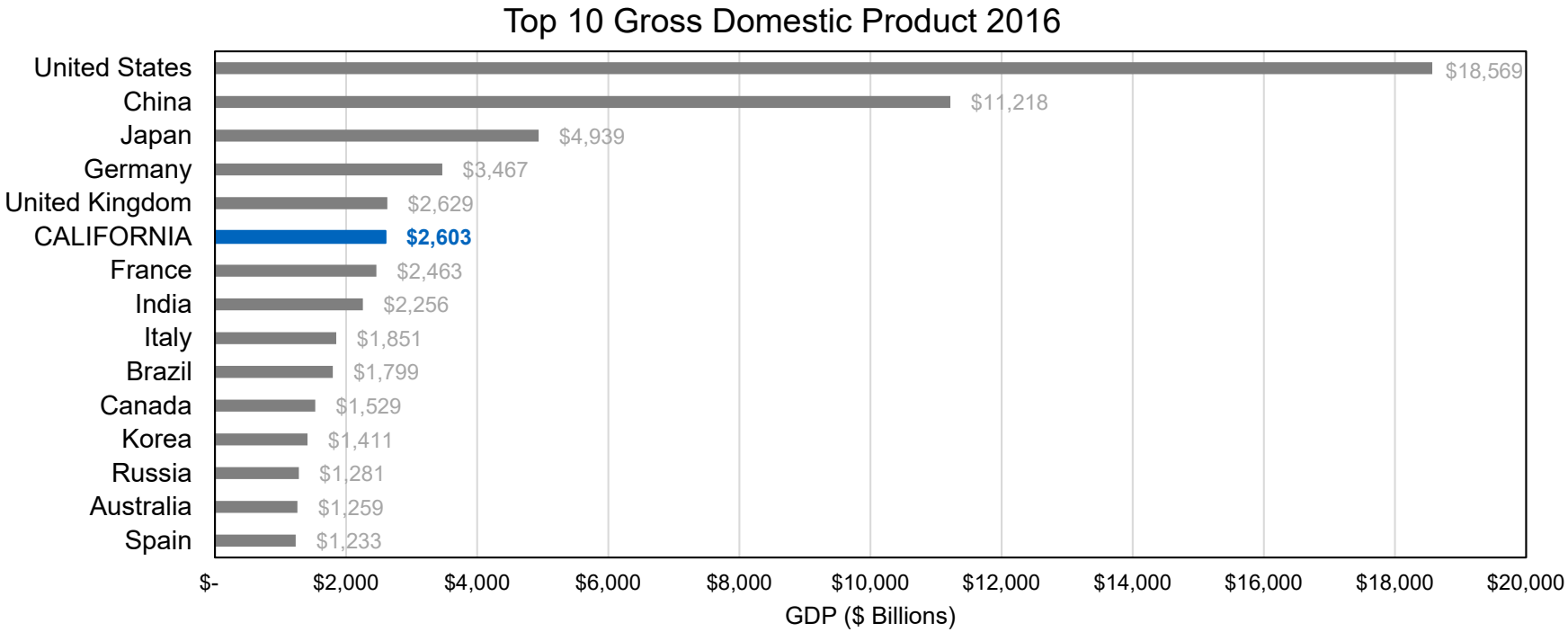
Background: California



Source: http://www.dof.ca.gov/Forecasting/Economics/Indicators/Gross_State_Product/

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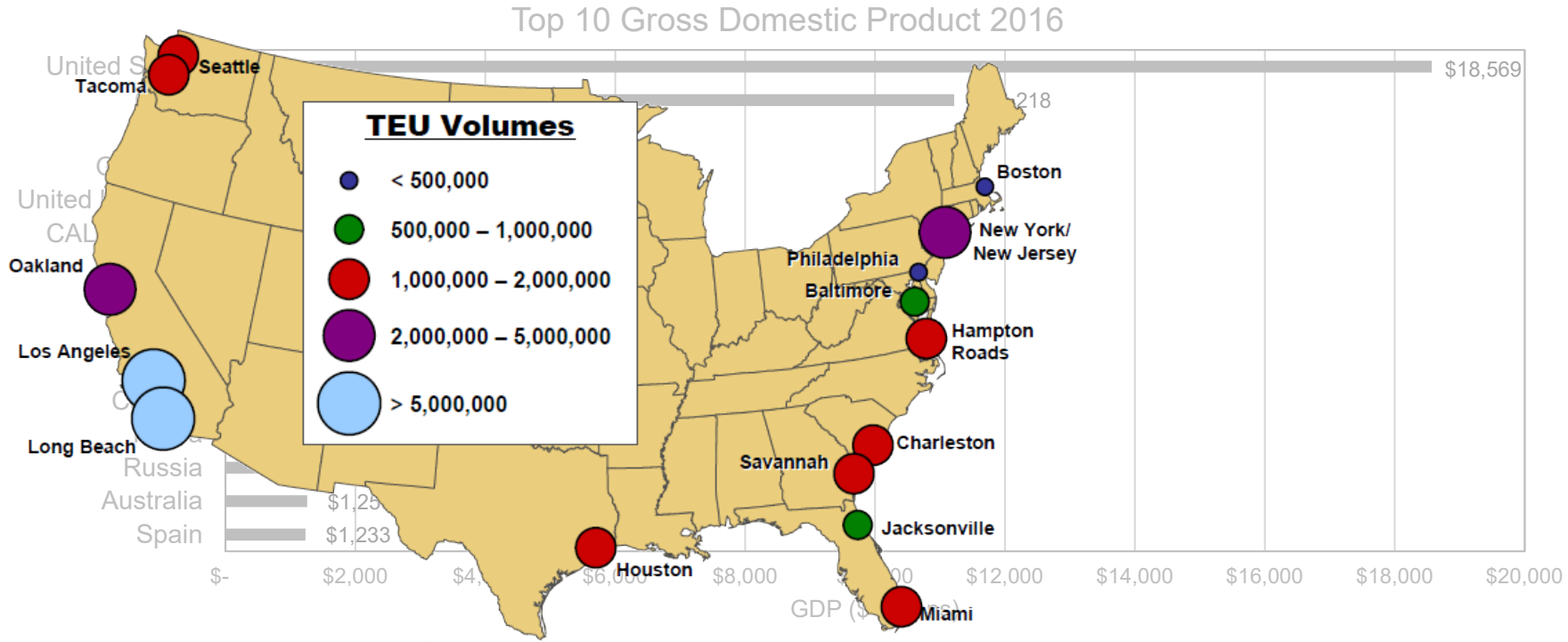

Source: http://www.virginiaplaces.org/transportation/graphics/portteus.png

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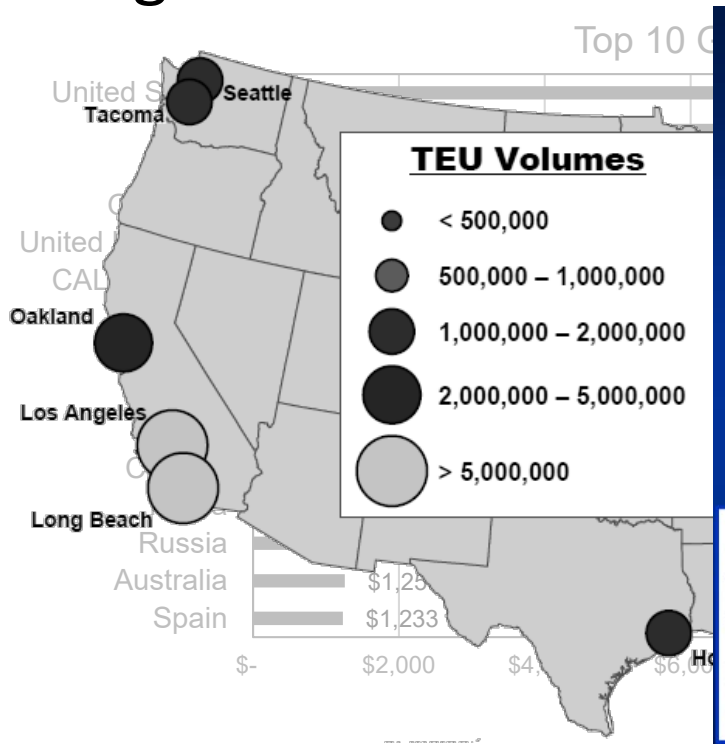

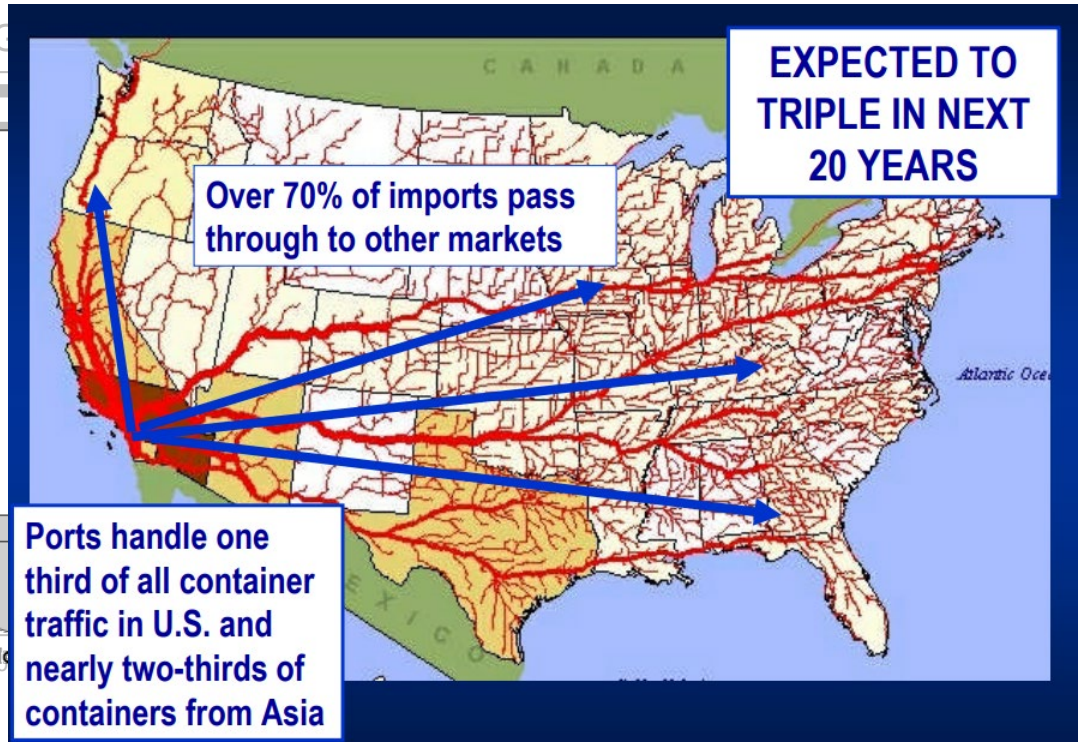

Source: https://secure.acce.org/clientuploads/uploadedfiles/Education_and_Events/Ford_RSD_Fellowship/Meeting3PisanoPresentation.pdf

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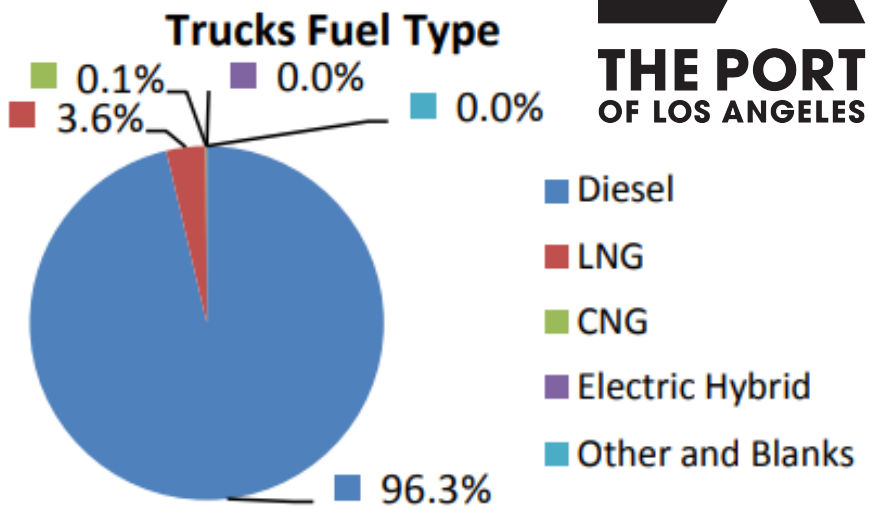
Background: Diesel



THE PORT OF LOS ANGELES

Source: https://www.roanoketrade.com/breaking-news-los-angeleslong-beach-port-trucks-to-vote-on-strike-tomorrow/
https://www.portoflosangeles.org/ctp/CTP_Monthly_Truck_Move_Analysis_March_2017.pdf

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Background: Diesel Particulate Matter (DPM)

International Agency for Research on Cancer

World Health Organization

IARC: DIESEL ENGINE EXHAUST CARCINOGENIC

Lyon, France, June 12, 2012 -- After a week-long meeting of international experts, the International Agency for Research on Cancer (IARC), which is part of the World Health Organization (WHO), today classified diesel engine exhaust as **carcinogenic to humans (Group 1)**, based on sufficient evidence that exposure is associated with an increased risk for lung cancer.

Source: https://www.iarc.fr/en/media-centre/pr/2012/pdfs/pr213_E.pdf

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Background: Diesel Particulate Matter (DPM)

International

World Organ

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Agency for Resear
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on (WHO), today
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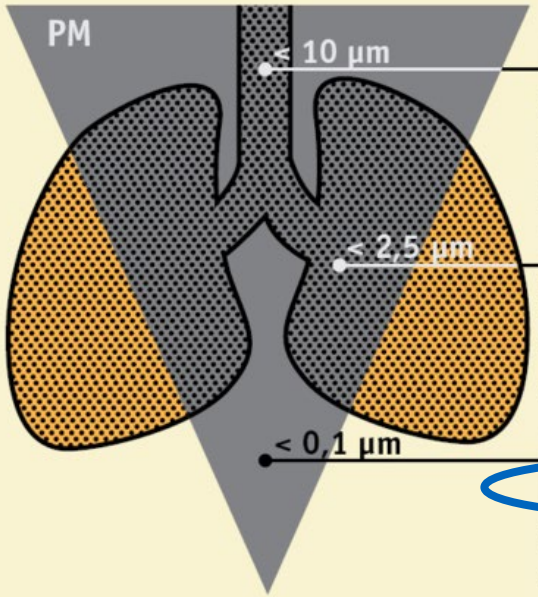
Types and effects of particulate matter



Fine particulate inhalable
Street dust, abrasion
» Respiratory ailment
» Decrease of pulmonary function

Fine particulate respirable
Industrial dust, exhaust
» Dermatologic diseases
» Increased risk of lung cancer

Ultra fine particles
Diesel soot, exhaust
» Increased risk of heart attacks
» Increased risk of cancer

Source: http://www.clean-heat.eu/en/background/particulate-matter.html

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Background: Diesel Related Regulations (CA)

2000	• Regulations introduced to reduce air pollution from transit buses • Comprehensive plan approved to reduce PM emissions from diesel equipment
2001	• Standards passed reducing diesel soot and smog-forming emissions by 90% from new diesel engines, to take into effect in 2007 MY engines

2002	• Lower PM standards adopted
	  ○ PM_{10} annual average: 20 µg/m³
	  ○ PM_{10} 24h average: 50 µg/m³
	  ○ $PM_{2.5}$ annual average: 12 µg/m³
	  ○ $PM_{2.5}$ 24h average: 25 µg/m³

2003	• Sulfur content in diesel fuel required to have 95% reduction
2004	• Low sulfur rule adopted for intrastate locomotives and harbor crafts • Idling time for HDDT limited to five minutes of non-essential idling
2005	• Regulation adopted requiring installation of diagnostic systems on all HDDT starting at engine MY 2010, which will reduce NO_X emissions by 100 tons/day • Memorandum of Understanding (MOU) signed with Union Pacific and Burlington Northern Santa Fe Railroads to reduce diesel emissions in and around rail yards
2006	• Diesel fuel switched to new Ultra Low Sulfur Diesel fuel (ULSD) • Comprehensive plan developed by POLA, POLB, US EPA, CARB, and SCAQMD to reduce air pollution and associated risks from port-related activities

2007	• Stricter NO_2 standards adopted
	  ○ 1h average: 0.18 ppm
	  ○ Annual average: 0.030 ppm
	• Statewide Drayage Truck Regulation approved, requiring lower emissions from port and rail bound or originated drayage trucks

2008	• Truck and Bus Rule approved, requiring installation of DPF or engine replacements and retrofits • Clean Truck Program launched at POLA/POLB
2009	• Regulation mandated ocean-going vessels (OGV) within 24 nautical miles of California's coastline to burn cleaner fuel which reduces SO_X and NO_X and DPM • Comprehensive Truck Management Plan approved at Port of Oakland
2010	• Diesel emissions reduced from four of the busiest railyards in the state • Diesel regulations are amended to further protect public health
2011	• Shore power made available for docked ships so idling is no longer needed • Funding assistance offered to truckers and buyers of on- and off-road clean vehicles

(See Appendix A of paper)

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Prop 1B passed. Aids in emissions reduction in trade corridors

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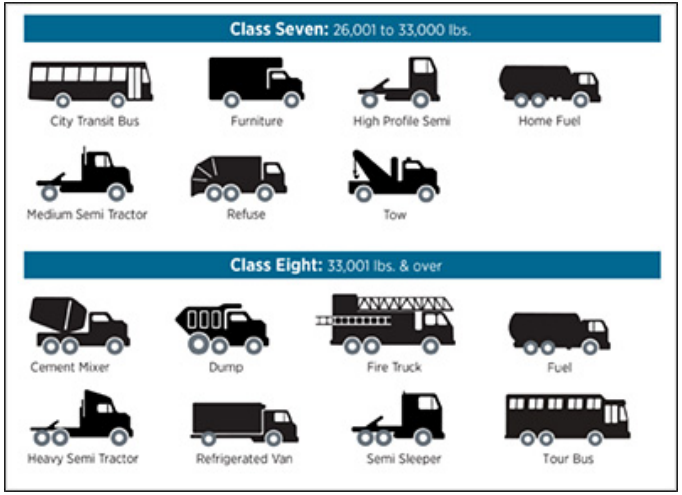
Drayage Truck Regulation:

Class 7 and 8 trucks must see 85% DPM reduction by 2020



Source: http://nhcleancities.org/wp-content/uploads/2016/04/image.jpg

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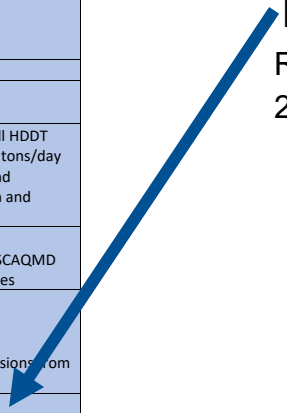

Truck and Bus Rule:

Reduce NO_X emissions by achieving 2010 MY engines by 2020

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Each port has own "Clean Air" Plan

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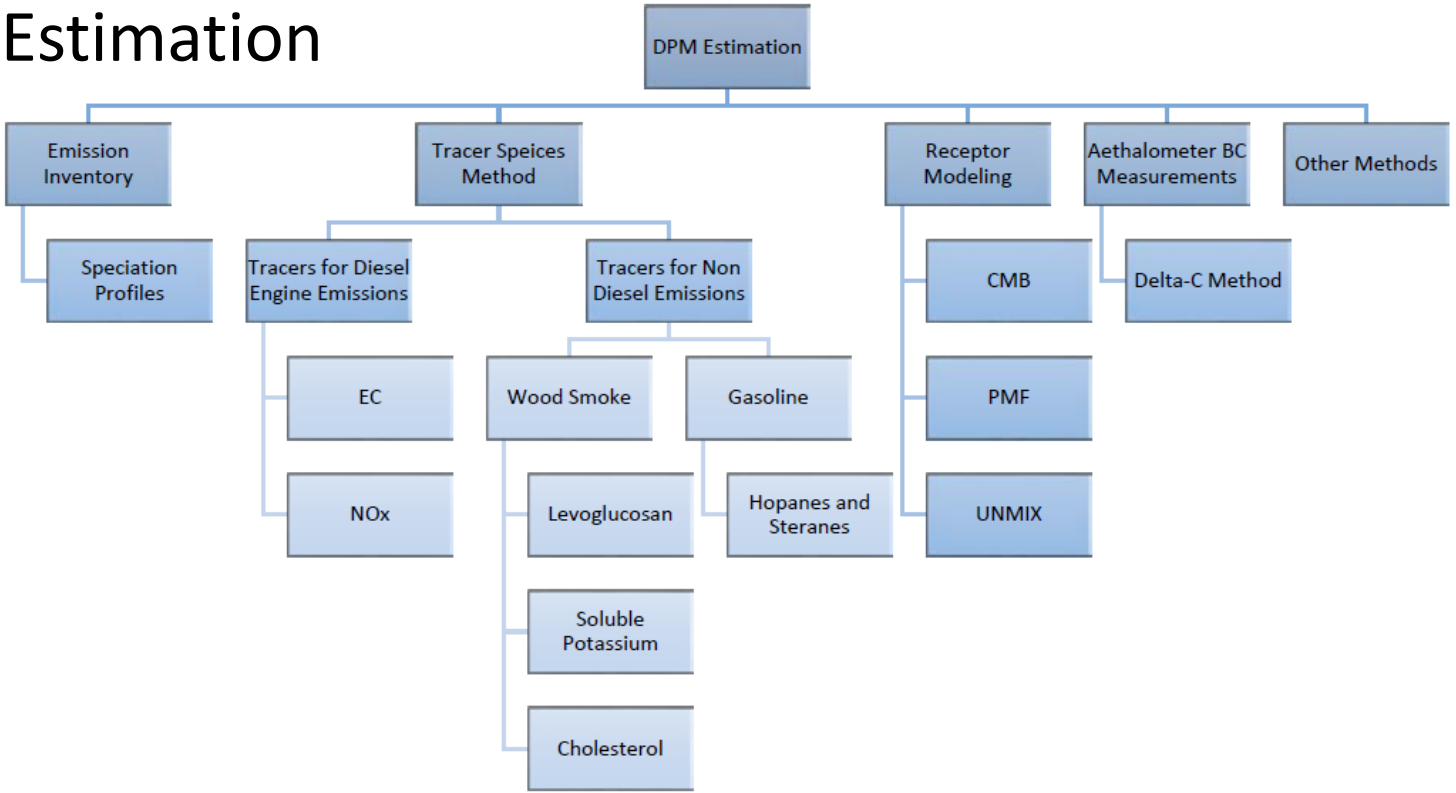
DPM Estimation



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DPM Estimation: Past Methods

- PM_{10} Ratio (1998)
- Emission Inventory Ratio (2000)
- Chemical Mass Balance (CMB) (2008)
- DPM-to-NO_X Ratio (2010)
- DPM-to-EC Ratio (2015)

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DPM Estimation: Past Methods

- PM_{10} Ratio (1998)
- Emission Inventory Ratio (2000)
- Chemical Mass Balance (CMB) (2008)
- DPM-to-NO_X Ratio (2010)
  - CARB (Truck and Bus Regulation)
  - α based off two year-long, and a few short-term CMB studies
  - Uncertainties:
    - No single source profile
    - Oxidation of molecular markers
    - Differences in carbon measurement method
- DPM-to-EC Ratio (2015)

$$DPM = \alpha \, NO_{X\,annual\ average}$$

$$\alpha = \frac{DPM_{2.5}}{NO_{X\,total\ ambient}}$$

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DPM Estimation: Past Methods

- PM_{10} Ratio (1998)
- Emission Inventory Ratio (2000)
- Chemical Mass Balance (CMB) (2008)
- DPM-to-NO_X Ratio (2010)
- DPM-to-EC Ratio (2015)
  - SCAQMD (MATES IV)
  - Based off
    - PM speciation profiles
      - From dynamometer tests and source testing
    - Source testing profiles

$$\frac{PM_{diesel}}{EC_{total}} = \frac{PM_{diesel}}{EC_{diesel}} \times \frac{EC_{diesel}}{EC_{total}}$$

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Combined Alpha Method

Combines DPM-to-NO_X Ratio and DPM-to-EC Ratio methods

$$DPM = \alpha\, NO_{X\,annual\ average}$$

$$\alpha = \frac{DPM_{2.5}}{NO_{X\,total\ ambient}}$$

$$\frac{PM_{diesel}}{EC_{total}} = \frac{PM_{diesel}}{EC_{diesel}} \times \frac{EC_{diesel}}{EC_{total}}$$

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Combines DPM-to-NO_X Ratio and DPM-to-EC Ratio methods

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$$\frac{PM_{diesel}}{EC_{total}} = \frac{PM_{diesel}}{EC_{diesel}} \times \frac{EC_{diesel}}{EC_{total}}$$

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Combined Alpha Method: Calculations

Combines DPM-to-NO_X Ratio and DPM-to-EC Ratio methods

1. Calculate α with:
   - DPM estimation from MATES IV
   - 2012 basin-wide NO_X average

$$\alpha = \frac{DPM_{2.5}}{NO_{X\,total\ ambient}} = \frac{0.95\ \mu g/m^3}{32.8\ ppb} = 0.029$$

2. Calculate average annual NO_X
   - Two different NO_X datasets:
     - CARB's Air Quality and Meteorological Information System (AQMIS)
     - 7 "Select Sites"
       - 3 near road
       - 4 urban
3. DPM is product of α and NO_X

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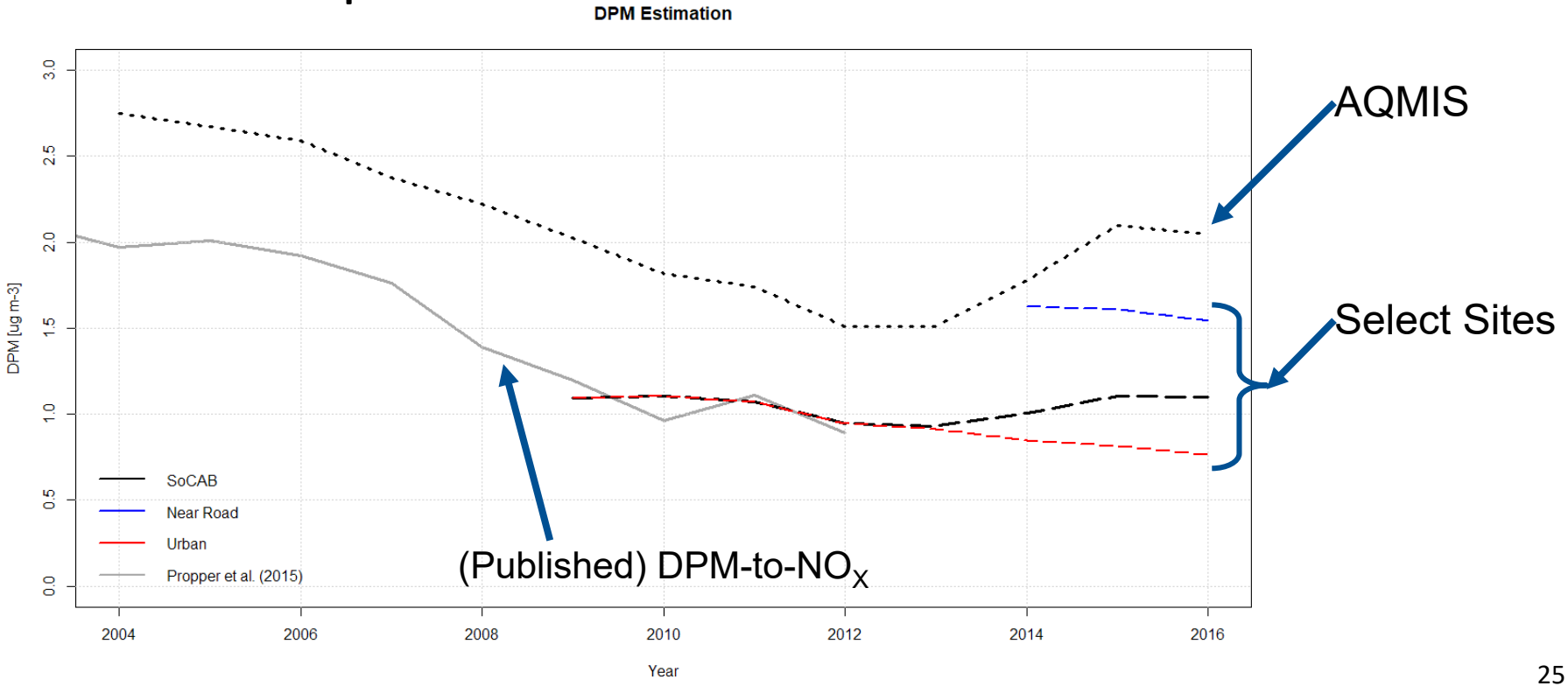
Combined Alpha Method: Calculations



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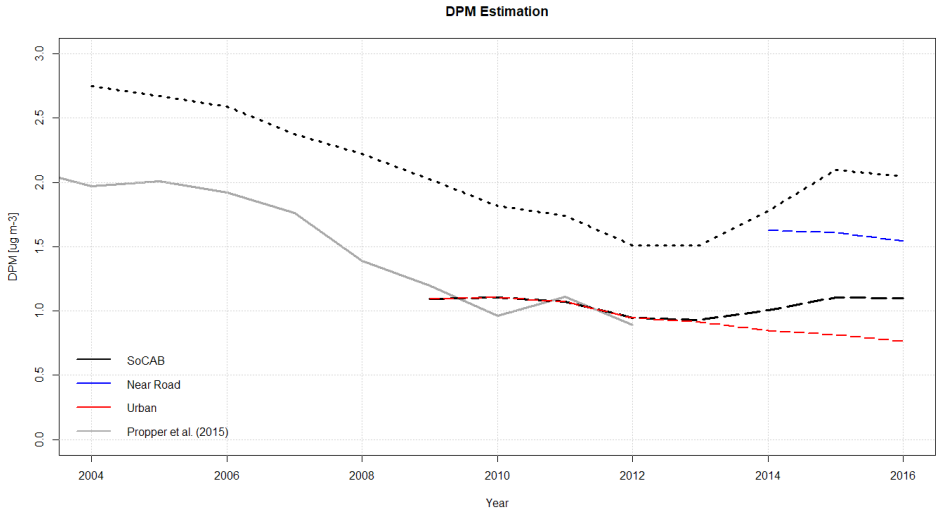
Combined Alpha Method: Analysis

SoCAB not accurately represented

- AQMIS higher than Select Sites
  - AQMIS: highest value of daily average of 27 monitoring sites
    - Oftentimes influenced by near road



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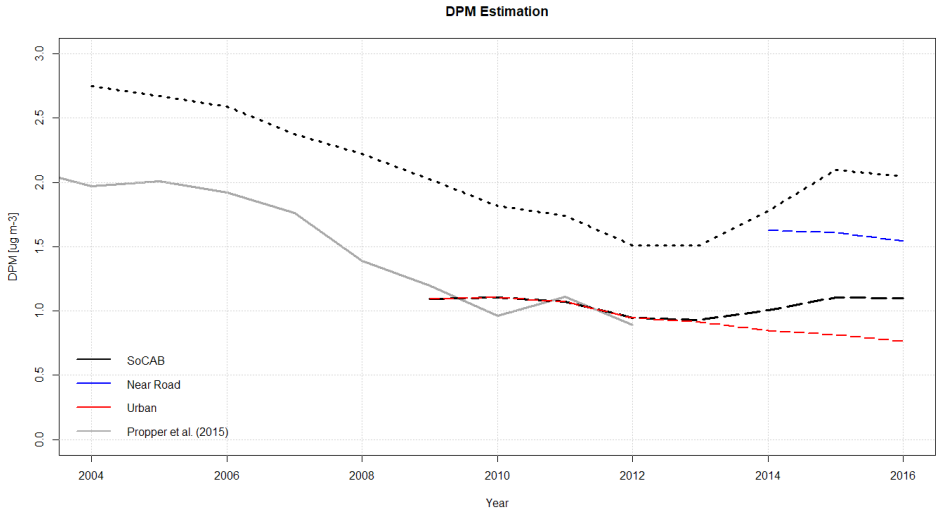
Combined Alpha Method: Analysis

SoCAB not accurately represented

- AQMIS higher than Select Sites
  - AQMIS: highest value of daily average of 27 monitoring sites
    - Oftentimes influenced by near road
  - NO_X from Select Sites more representative of SoCAB
  - DPM derived from AQMIS NO_X more representative of DPM*



* Will be examined in the next section

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Combined Alpha Method: Validity

Method	MATES II	MATES III	MATES IV
	4/1998 - 3/1999	4/2004 - 3/2006	7/2012 - 6/2013
EI	3.40	2.16	-
PM2.5	-	3.50	-
CMB	-	3.2 - 3.49	-
DPM/NOx	2.42 - 2.61	1.92 - 2.01	0.89
DPM/EC	-	1.24	0.95
Combined	-	2.58 - 2.75 (AQMIS)	1.5 (AQMIS) 0.94 (Select)

% Difference:
18%
15%

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Combined Alpha Method: Validity

Method	MATES II	MATES III	MATES IV
	4/1998 - 3/1999	4/2004 - 3/2006	7/2012 - 6/2013
EI	3.40	2.16	
PM2.5	-	3.50	-
CMB	-	3.2 - 3.49	-
DPM/NOx	2.42 - 2.61	1.92 - 2.01	0.89
DPM/EC	-	1.24	0.95
Combined	-	2.58 - 2.75 (AQMIS)	1.5 (AQMIS) 0.94 (Select)

Difference:

- 95%
- 2.26 µg/m^3

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Overview

1. Background
2. DPM Estimation Methods
3. Combined Alpha Method of estimating DPM
4. **NO_X to BC Correlation at three geographically different locations**
5. Conclusion

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NO_X to BC Correlation: Why NO_X?

NO_X

- Diesel engines emit more NO_X than do gasoline engines[a]
- Concentrations drop sharply on scales of tens to hundreds of meters[b]
- Levels reduced by SCR systems, but not during cold starts or low temperatures, speed, load, or urea levels[c]
- Not a unique tracer of DPM alone[d]

[a] Dallmann et al. (2013); [b] Gately et al. (2017); [c] Misra et al. (2013), Bishop et al. (2013), Preble et al. (2015); [d] CARB (2010)

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NO_X to BC Correlation: Why NO_X?

NO_X

Purpose

To determine validity of using NO_X in combination with EC to estimate DPM

Method

Examine correlation between NO_X and BC, a species known to represent DPM, at different sites to assure location independency

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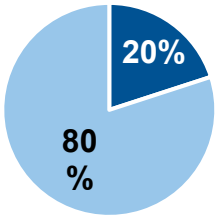
NO_X to BC Correlation: CA v. EU

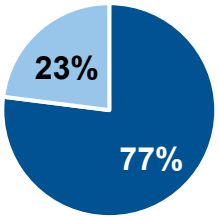
Fleet Makeup

Gasoline v. **Diesel**

CA



EU



Regulations

CA:

Fuel neutral

Fleet averages

EU:

Gasoline / diesel

Maximum limits

Stage	Date	NMOG	CO	NOx	PM	HCHO	HC+NOx
		g/km					
LEV I	1990	0.056	2.610	0.186	0.050	0.011	-
Tier 1	1991	0.193	2.610	0.373	-	-	-
LEV II	1998	0.056	2.610	0.044	0.006	0.011	-
LEV III	2012	0.056	2.610	0.044	0.006	0.002	-
Euro 1	1992	-	2.72 / 2.72	-	- / 0.14	-	0.97 / 0.97
Euro 2	1996	-	2.2 / 1	-	- / 0.08	-	0.5 / 0.7
Euro 3	2000	-	2.3 / 0.64	0.15 / 0.5	- / 0.05	-	- / 0.56
Euro 4	2005	-	1 / 0.5	0.08 / 0.25	- / 0.025	-	- / 0.3
Euro 5	2009	-	1 / 0.5	0.16 / 0.18	0.005 / 0.005	-	- / 0.23
Euro 6	2014	-	1 / 0.5	0.16 / 0.18	0.005 / 0.005	-	- / 0.17
Stage	Date	g/km					
		NMOG	CO	NOx	PM	HCHO	HC+NOx

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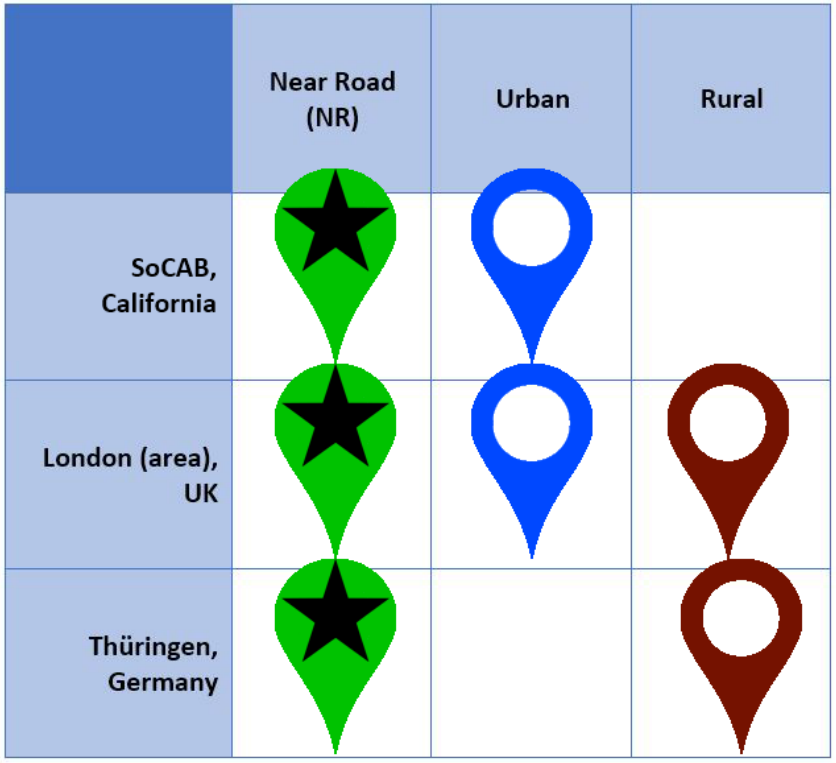
NO_X to BC Correlation: Locations

SoCAB, California

London (area), UK

Thüringen, Germany



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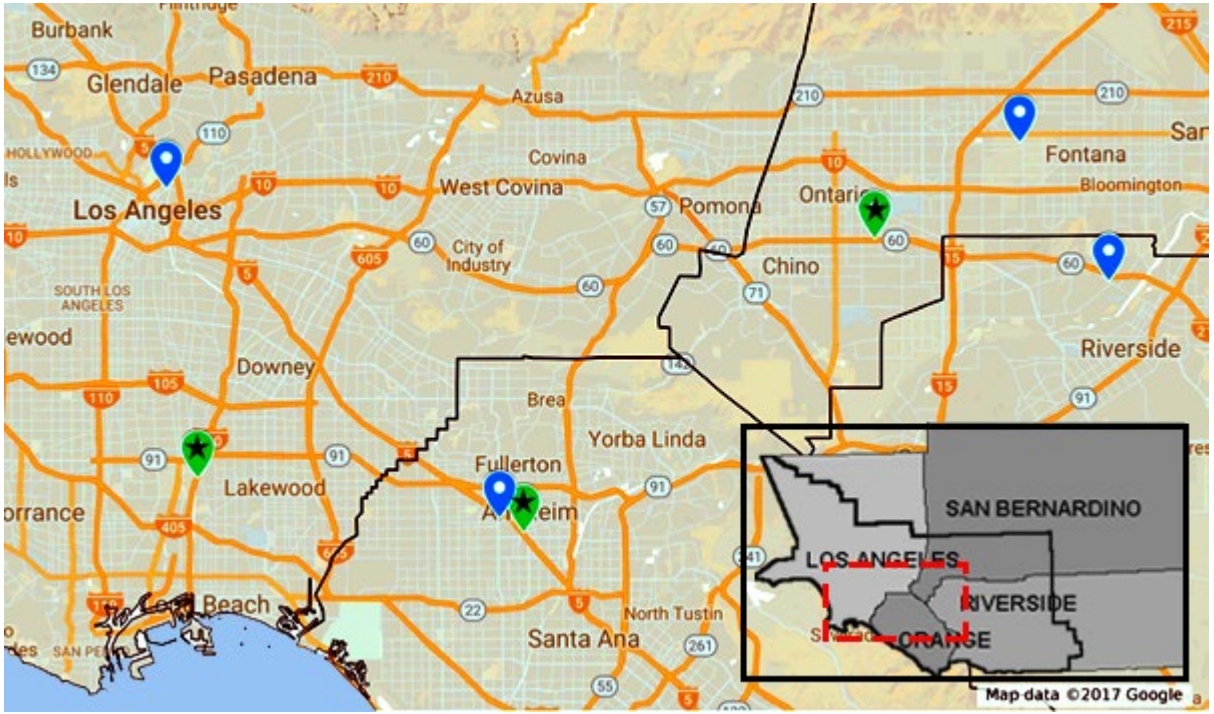

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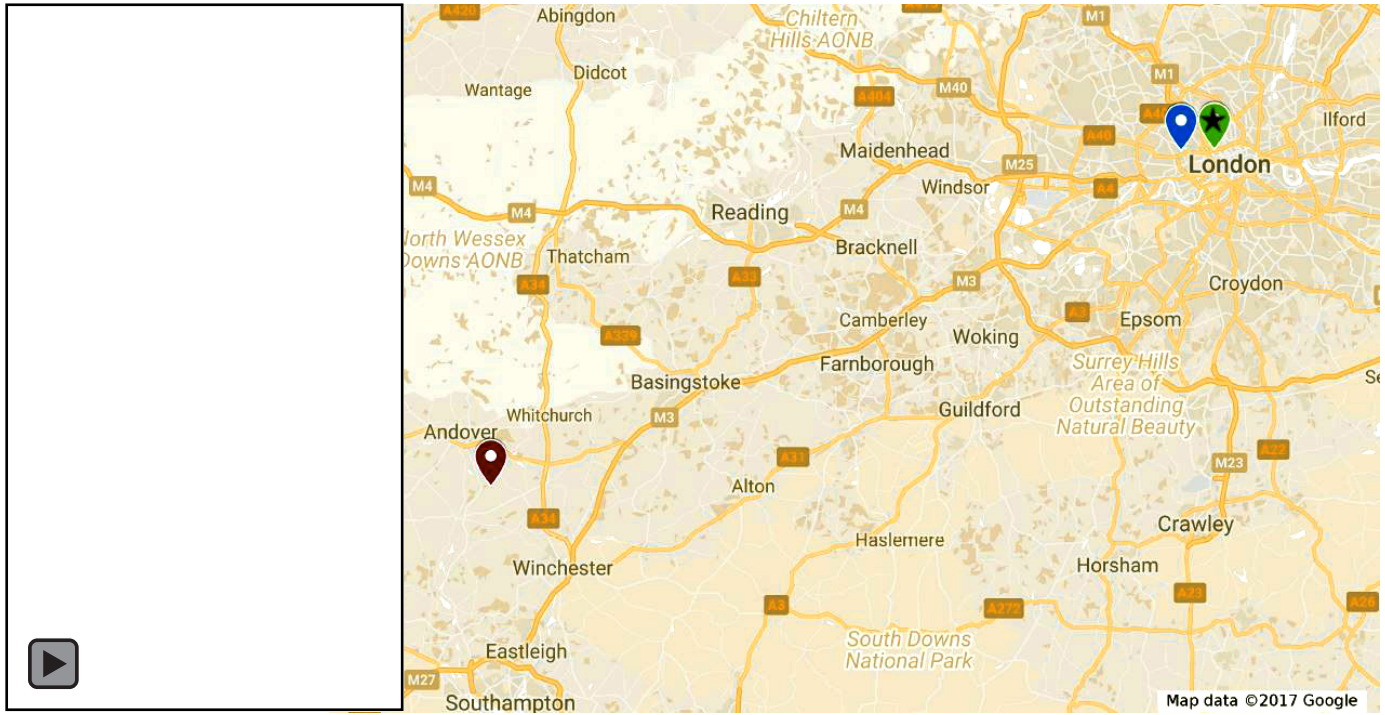

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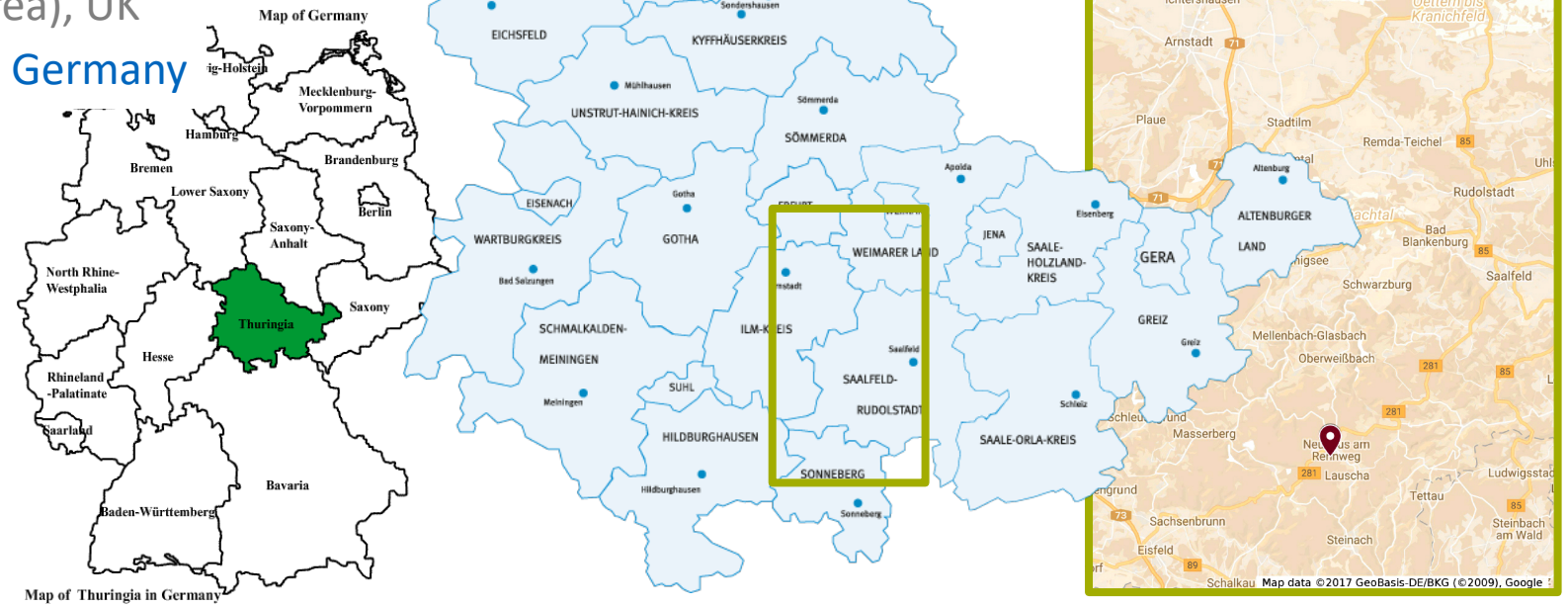

Source: http://www.thueringen-hilft.de/en/give-and-take/overview/

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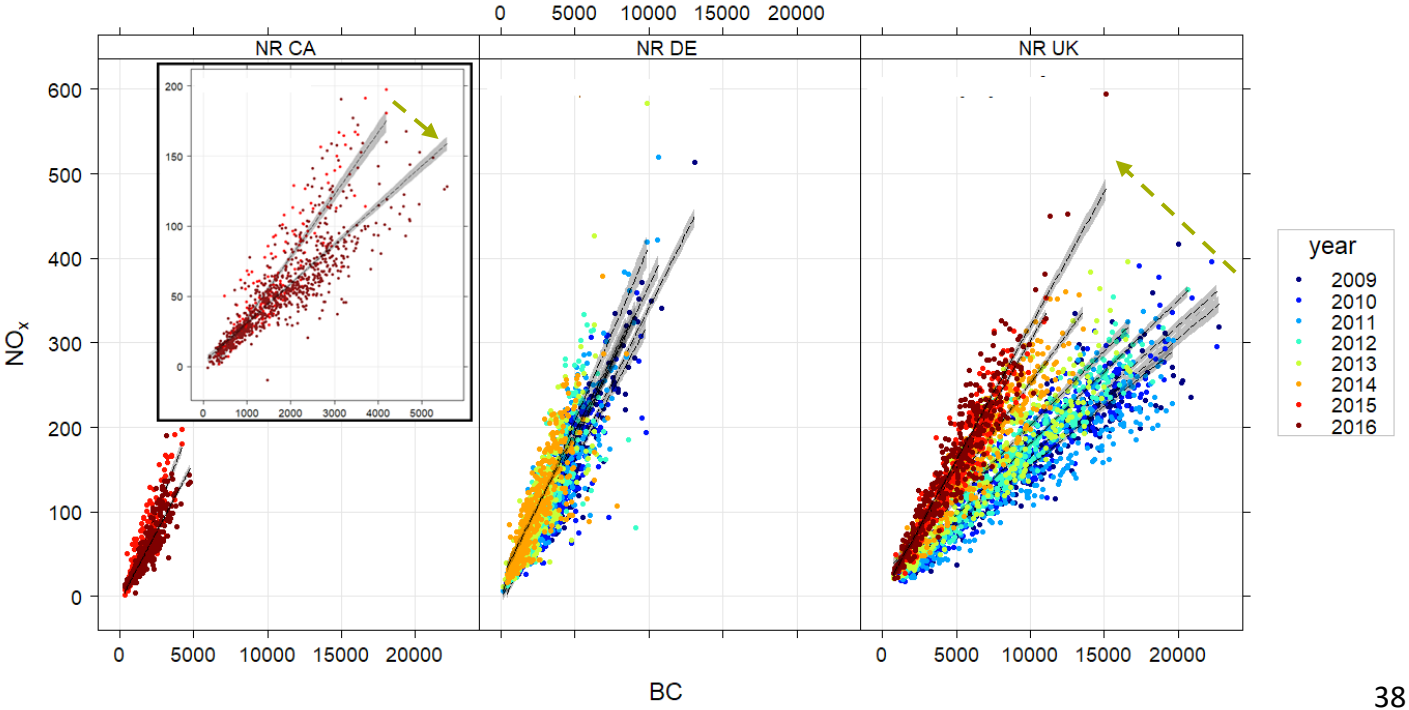
NO_X to BC Correlation: Near Road

Correlation is clear:

- $R^2 > 0.75$
- NO_X/BC (slope)
  - CA decreases
  - DE constant
  - UK increases
- Change in slope likely due to **BC** levels

Comparison of Near Road NO_x and BC Correlation



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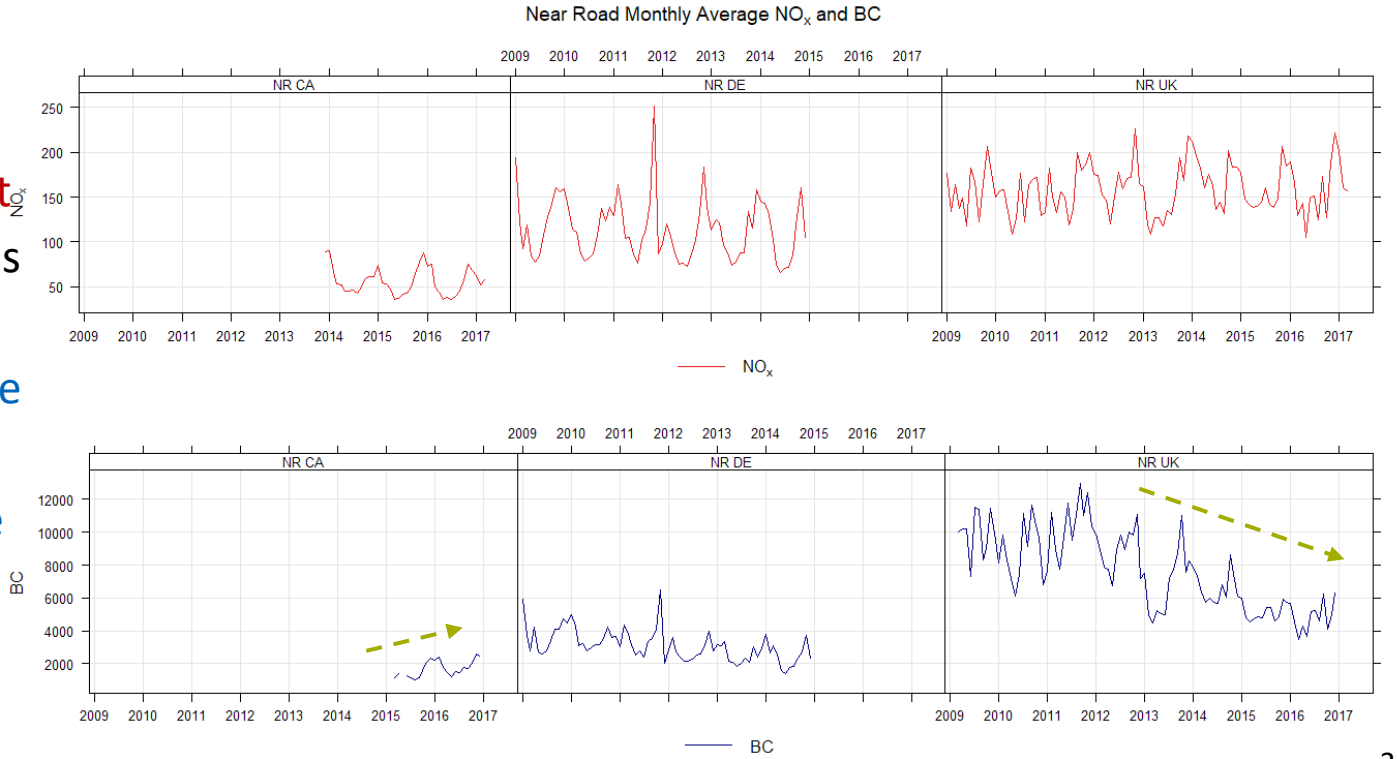
NO_X to BC Correlation: Near Road

NO_X/BC Ratio:

- NO_X
  - levels constant for all locations
- **BC**
  - Sharp decrease in UK
  - Slight increase in CA



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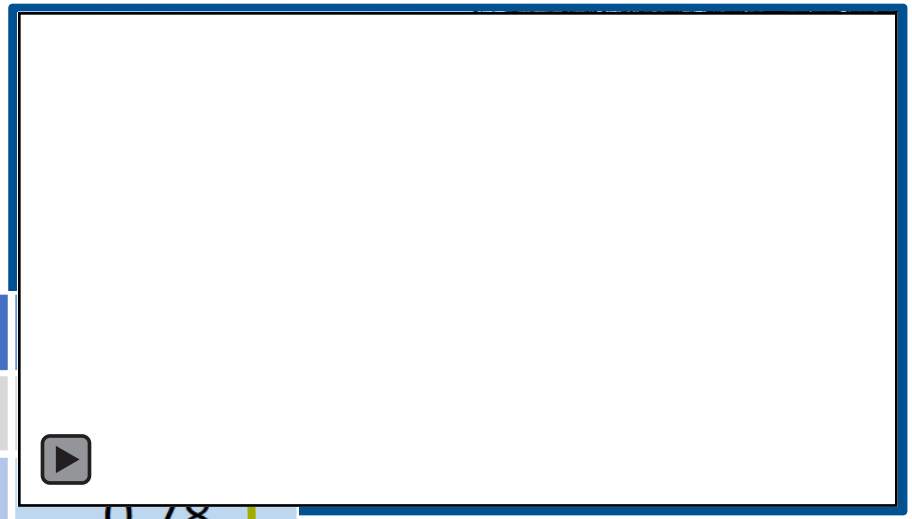
NO_X to BC Correlation: Near Road

California:

- Sunday
  - Less truck traffic[a]
  - R^2 drops



Near Road	CA	I-710	
	R^2	R^2	
Mon - Sat	0.73	0.84	0.78
Sun	0.69	0.79	0.56

[a] Traffic count and vehicle separation would provide additional insight on this correlation

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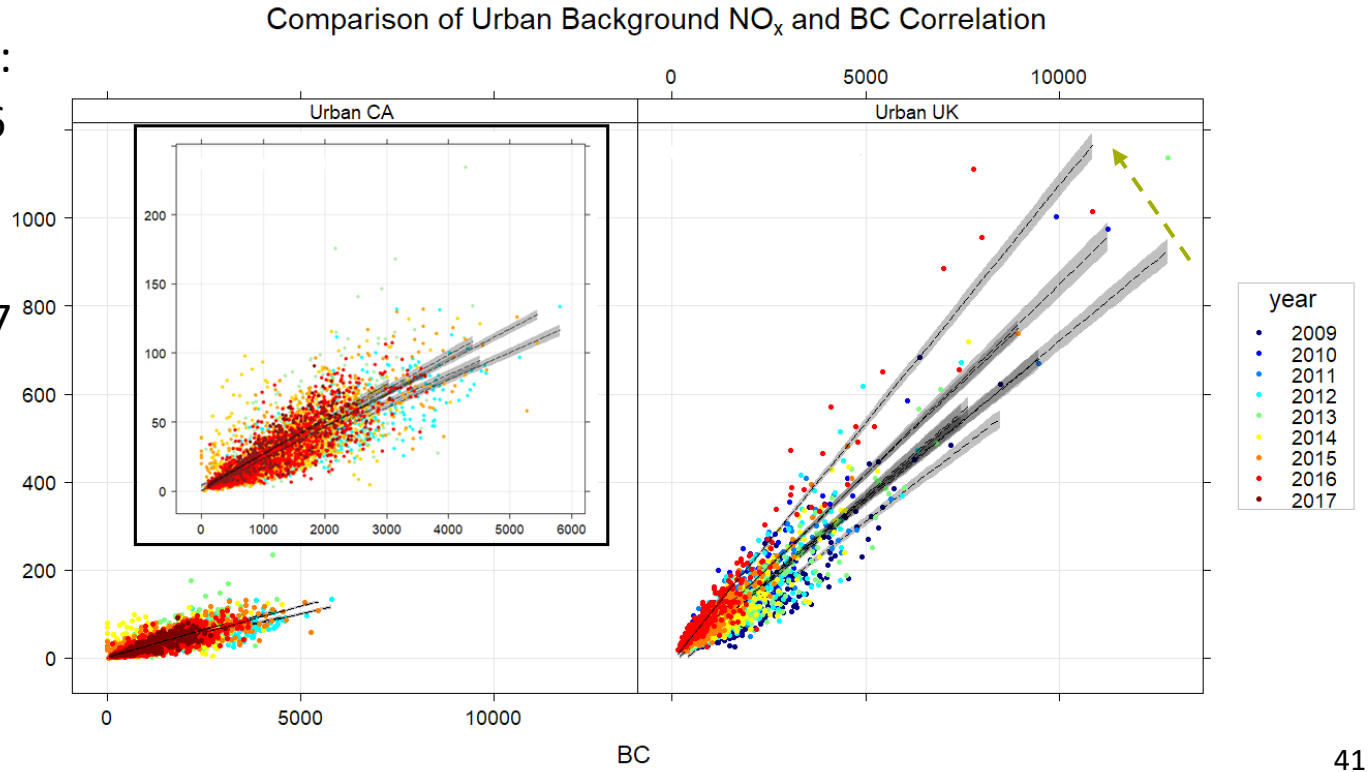
NO_X to BC Correlation: Urban

Correlation is present:

- CA R^2 average 0.66
  - Less diesel in urban areas
- UK Urban R^2 ~ 0.87
  - = UK NR R^2
  - Indicates same ratio of gas to diesel vehicles



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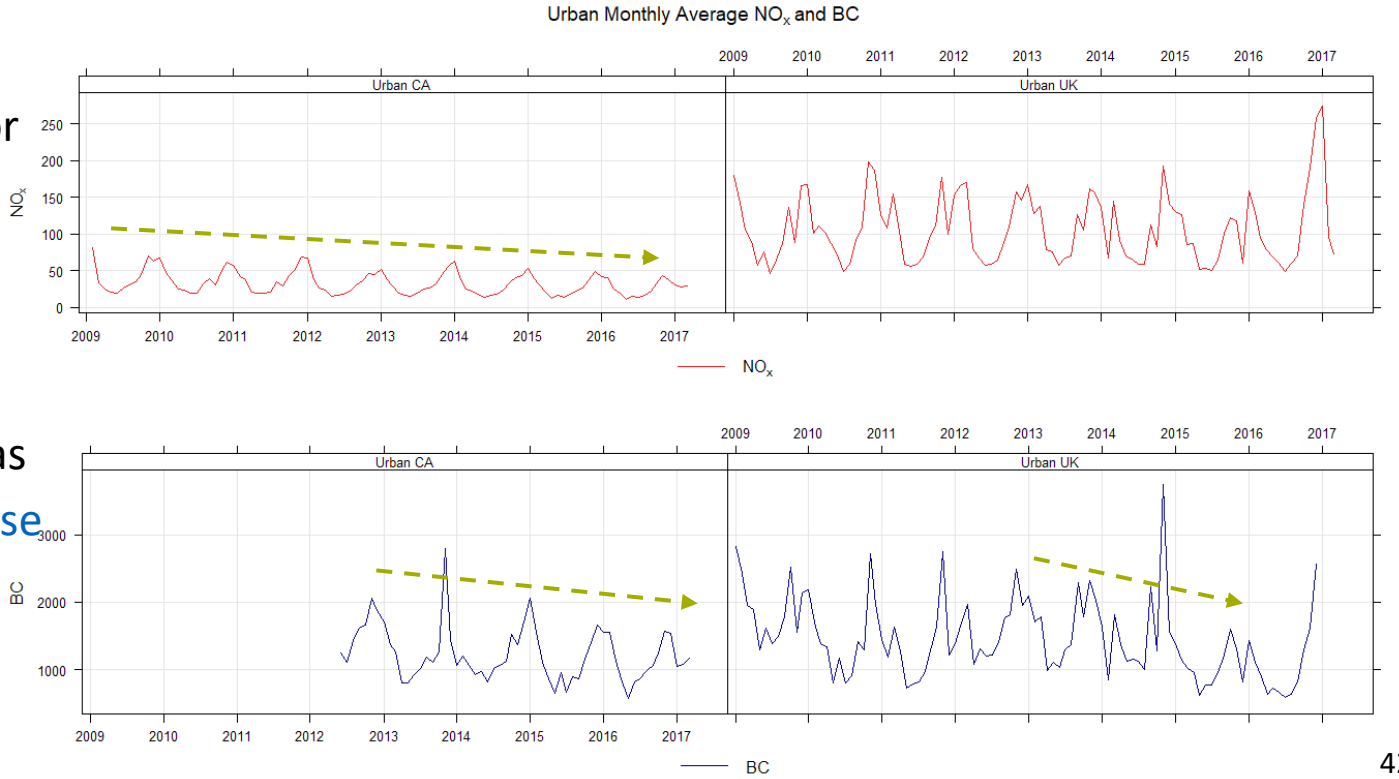
NO_X to BC Correlation: Urban

NO_X/BC Ratio:

- Very constant for CA (0.02)
  - Both NO_X and BC decrease
- Increase for UK
  - Same reason as NR: **BC** decrease



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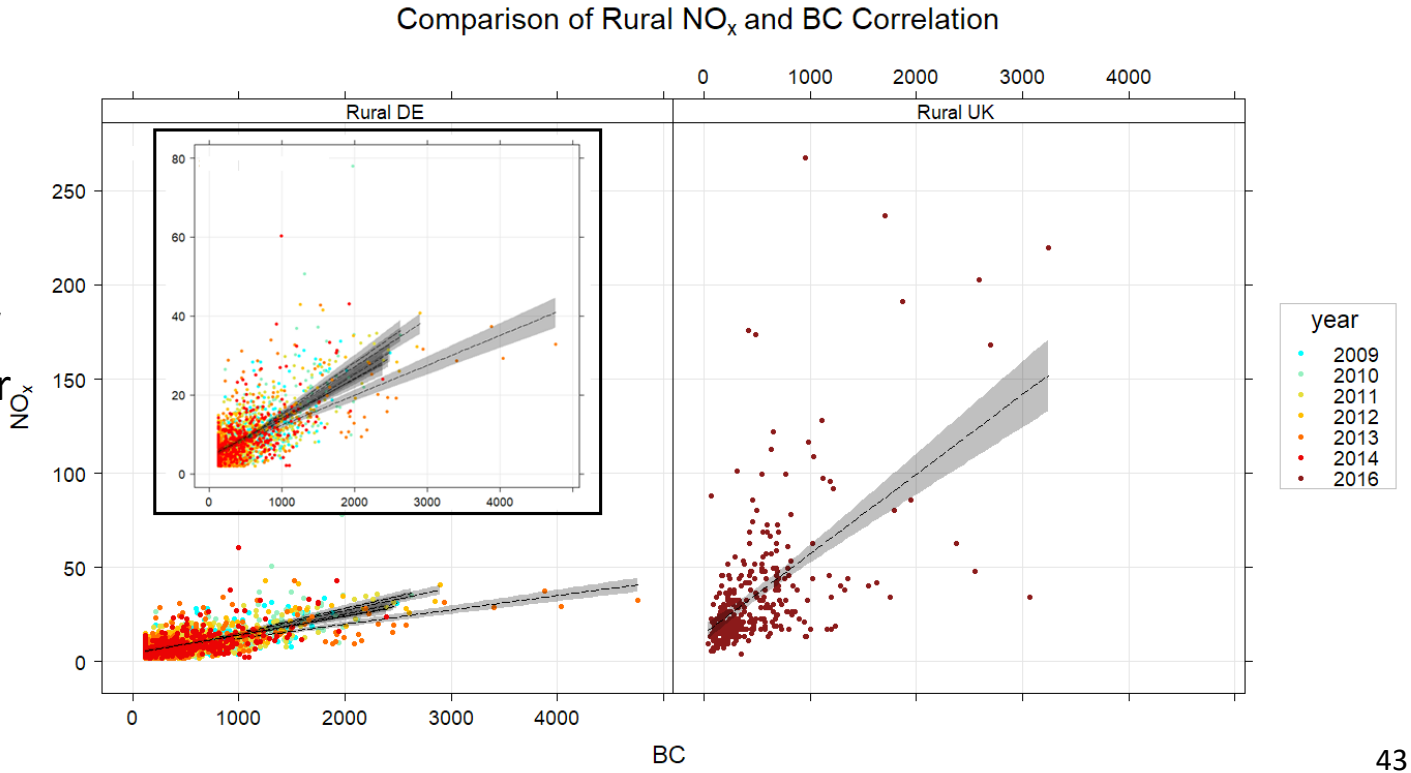
NO_X to BC Correlation: Rural

No correlation:

- No proximity to vehicular traffic
- Average $R^2 < 0.5$
- NO_X significantly lower than other sites



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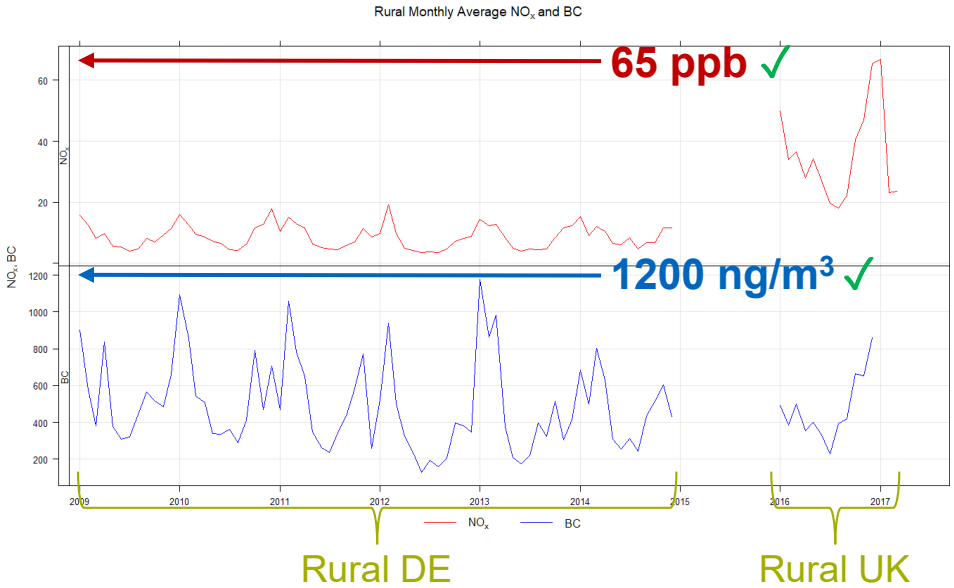
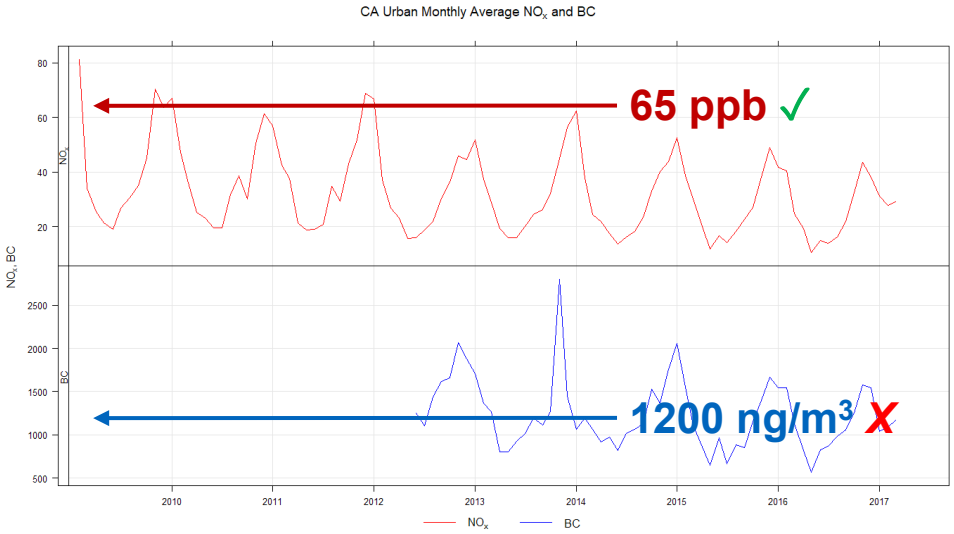
NO_X to BC Correlation: Rural

- Consistent low NO_X ✓
- No corresponding high BC ✓





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Conclusion

DPM Estimation: Combined Alpha Method

- Performed within 20% of existing methods
- Accuracy undetermined
- Can be improved with updated speciation and source testing profiles

NO_X-to-BC correlation can verify if using NO_X is valid

- Correlation **strong** at **near road** locations with diesel, **poor** at **rural** locations
- Low NO_X levels do not signify rural location (e.g. CA)
  - Low NO_X with corresponding low BC levels do
- Enhance with traffic count data

Acknowledgements

To my **family**: I send my love and gratitude.

To my **friends** near and far: I cherish our new and continued friendship.

To **Jorge Valentín Carreño Gatica**: I am inspired by your strength and determination. Thank you for your endless love and encouragement.

Thank You!

Questions