# TRECH STUDY
## TRANSPORTATION, EQUITY, CLIMATE & HEALTH

# On-road Sector Emissions Impact on $PM_{2.5}$ and $O_3$ – related Health Risks in the Northeast and Mid-Atlantic U.S.

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19th Annual CMAS Conference, October 26th-30th , 2020

All results presented here are preliminary and draft. Do not Cite or Share

Arter et al, In Prep 2020

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# TRECH Study

Co-benefits study that **aims to quantify spatial distribution of health benefits** from active transport and air quality improvements across the Northeast/Mid-Atlantic due to the Transportation Climate Initiative

Physical Activity | Air Quality | Health | Equity



TRECH, Transportation, Equity, Climate & Health, https://www.hsph.harvard.edu/c-change/news/trechstudy/

# TRECH Study

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# Project Overview

**Study**

- Perform a full emissions-to-impact benefits assessment for on-road vehicles in the TCI region

**Methods**

- Utilize sensitivity analyses to determine contribution from on-road vehicle emissions to regional fine particulate matter ($PM_{2.5}$) and ozone ($O_3$)

**Results**

- Quantify the number of adverse health outcomes from $PM_{2.5}$ and $O_3$ attributable to on-road vehicular emissions in the TCI region



$PM_{2.5}$, Fine Particulate Matter with aerodynamic diameter <2.5 microns; $O_3$, ozone; TCI, Transportation Climate Initiative.

# Methods – Air Quality

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**CMAQ** — Photochemical air quality model that estimates the pollutant concentrations across spatial and temporal **domain**
- **Version 5.2**

**DDM** — Sensitivity analysis that calculates incremental change in pollutant concentrations with respect to model input (**emissions**) across the domain to estimate how sensitive pollutant concentrations are to emissions

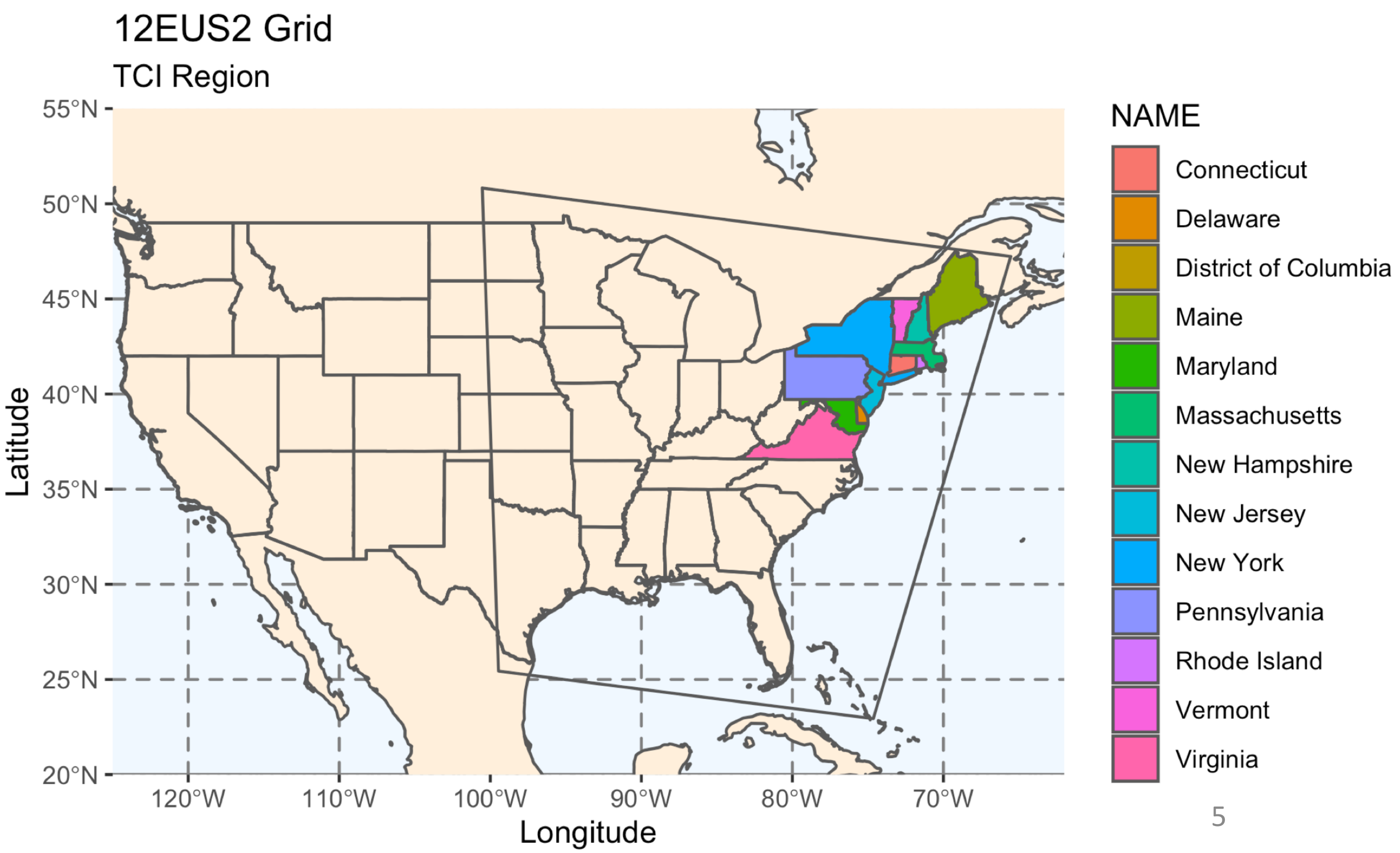
## Emissions

| | |
|---|---|
| **Source Regions** | CT, DC, DE, MA, MD, ME, NH, NJ, NY, PA, RI, VA, VT, BALMSA, BOSMSA, NYMSA, PHILMSA |
| **Vehicles** | LDA, LDT, MDT, HDT, BUS |
| **$PM_{2.5}$** | $NO_X$, VOC, $SO_2$, $NH_3$, PPM<br>**17 x 5 x 5 = 425 sensitivities** |
| **$O_3$** | $NO_X$, VOC<br>**17 x 5 x 2 = 170 sensitivities** |

## Domain

**Spatial**
12 x 12 km grids across the Eastern half of the U.S.

**Temporal**
Model is run for January and July 2016



# Methods – Health

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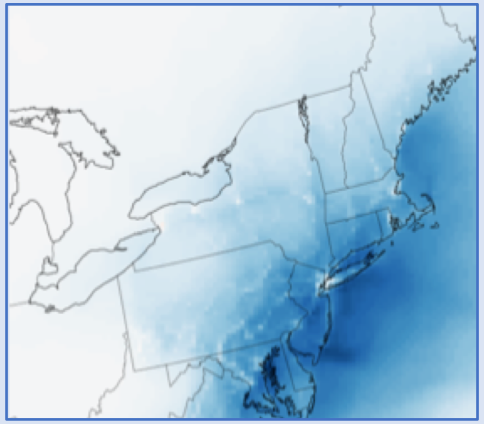
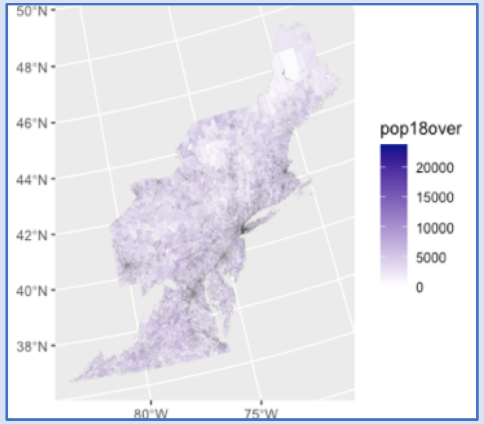
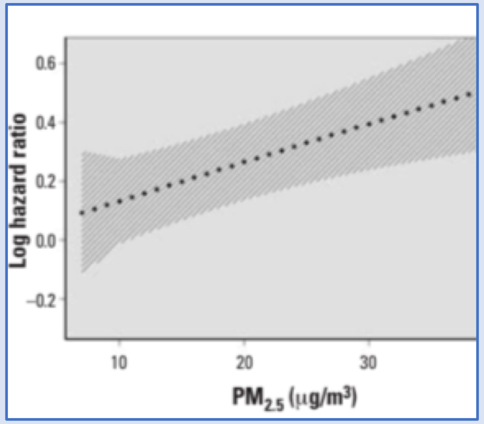
**BenMAPR**

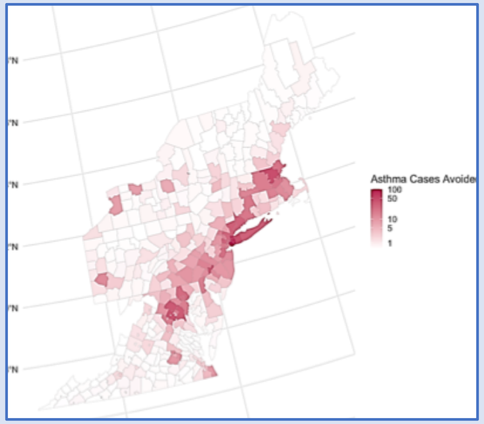
The health impact assessment tool used here is a version of BenMAP (from the U.S. EPA) but modified to work in the statistical computing language R

**Changes in Air Quality + Population and Background Health Data + Epidemiology = Health Benefits**





## Health outcomes evaluated

- $PM_{2.5}$ - attributable all-cause mortality
- Vodonos et al., *Environmental Research*, 2018

- $O_3$ - attributable all-cause mortality
- Turner et al., *American Journal of Respiratory and Critical Care Medicine*, 2016

# Emissions – Broad Overview

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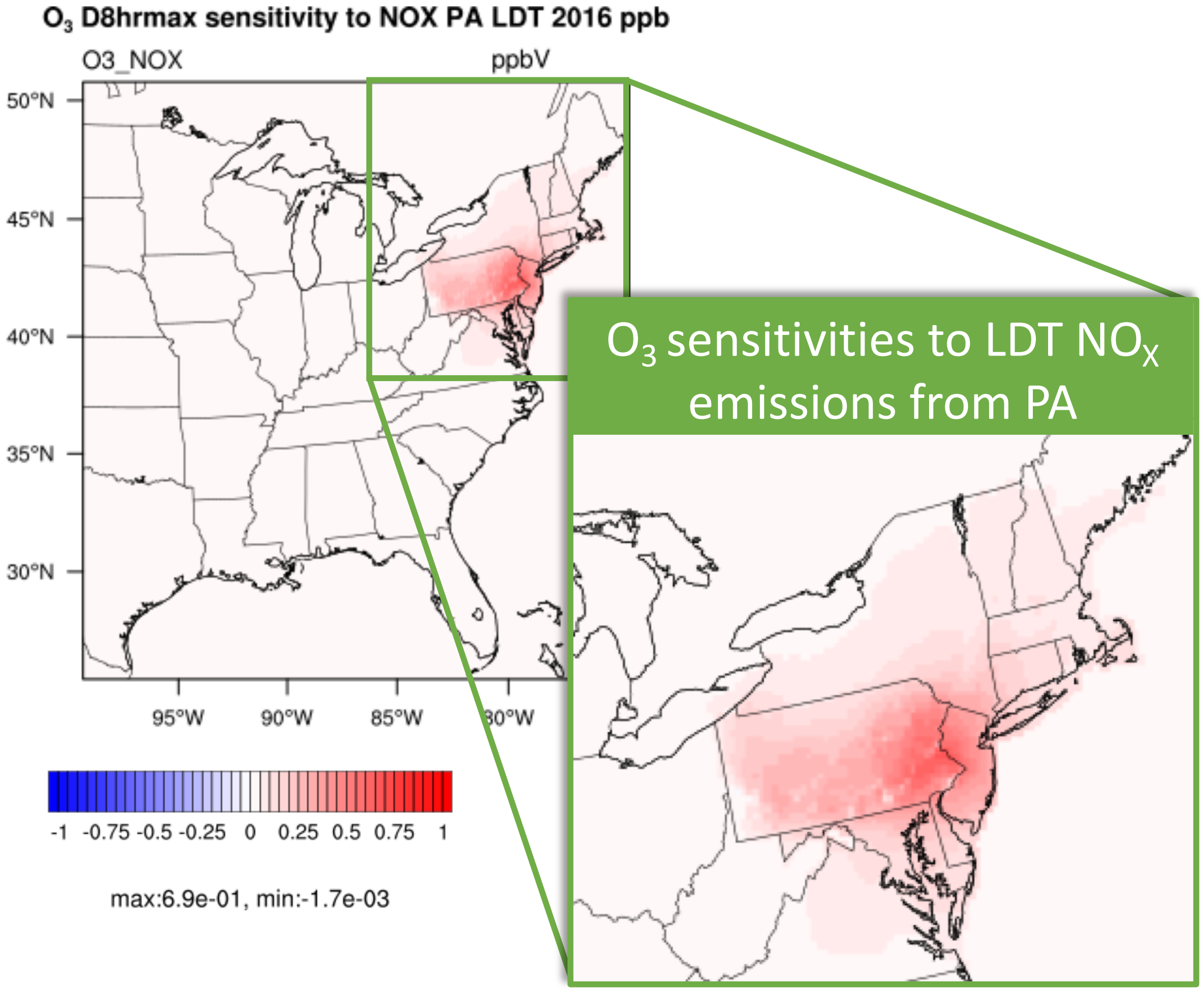
| | Vehicle Class | | | Source Region | | |
|---|---|---|---|---|---|---|
| Precursor | Largest Vehicle Class | January (Tons) | July (Tons) | Largest Source Region | January (Tons) | July (Tons) |
| $NO_X$ | LDT | 14,139 | 17,184 | Pennsylvania | 8,071 | 10,440 |
| VOC | LDT | 16,630 | 15,755 | Pennsylvania | 7,463 | 7,008 |
| $SO_2$ | LDT | 219 | 282 | New York | 99 | 134 |
| $NH_3$ | LDA | 581 | 740 | New York | 243 | 327 |
| PPM | LDA[a], HDT[b] | 417[a] | 456[b] | New York | 348 | 311 |

**We can quantify the largest source of precursor emissions by vehicle class and source region**

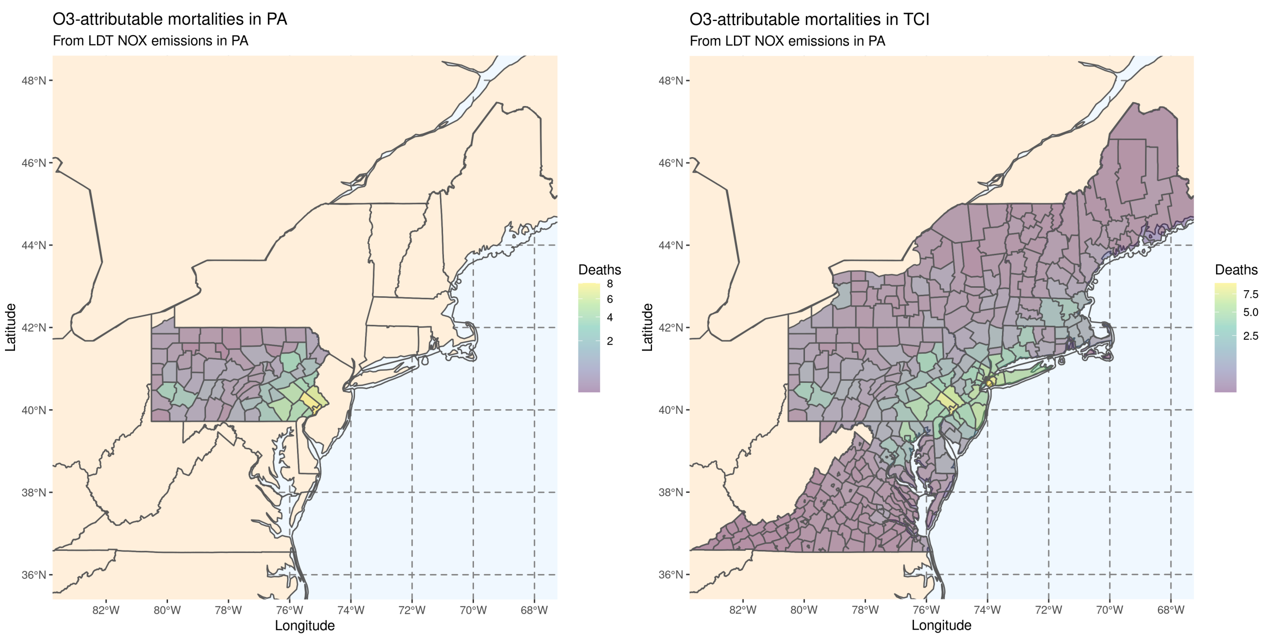


HDT, Heavy Duty Trucks; LDA, Light Duty Automobiles; LDT, Light Duty Trucks; $NH_3$, Ammonia; $NO_X$, Nitrogen Oxides; PPM, Primary Particulate Matter; $SO_2$, Sulfur Dioxide; VOC, Volatile Organic Compounds.

# Sensitivities – $O_3$




## $O_3$-attributable premature mortalities within the state and across the entire TCI region due to PA LDT $NO_X$



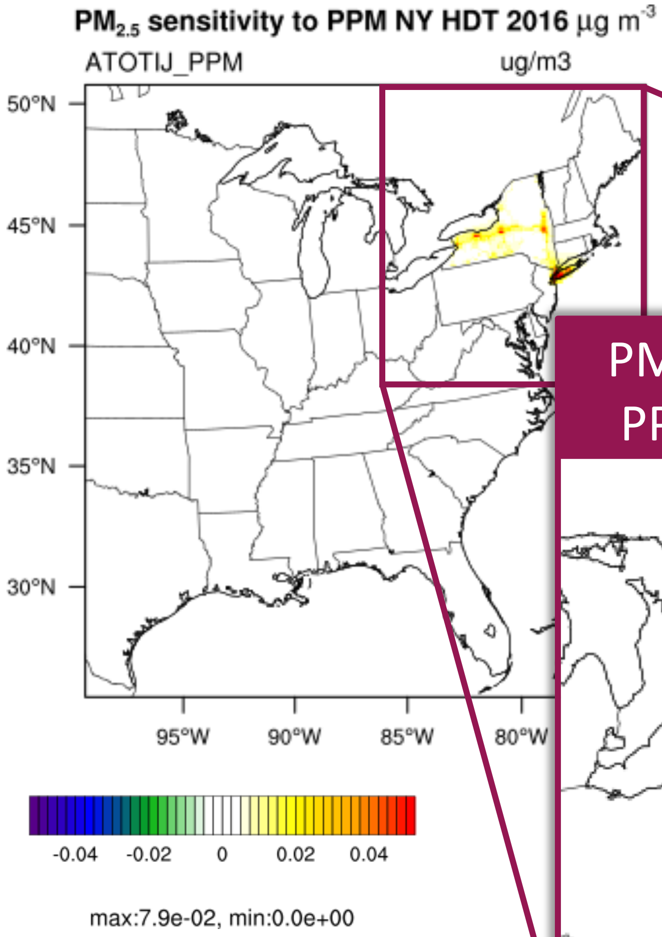

**This is an instance of air quality/health impacts <u>occurring downwind of the source region</u>**



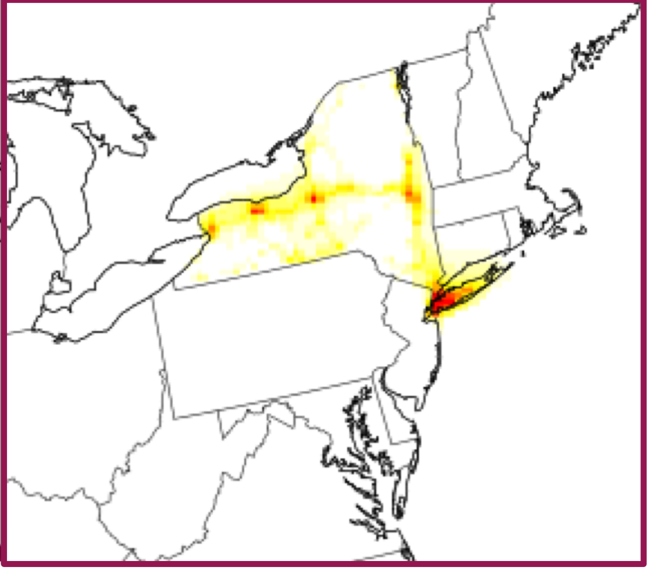
LDT, Light Duty Trucks; $NO_X$, Nitrogen Oxides; $O_3$, ozone; TCI, Transportation Climate Initiative.

# Sensitivities – $PM_{2.5}$

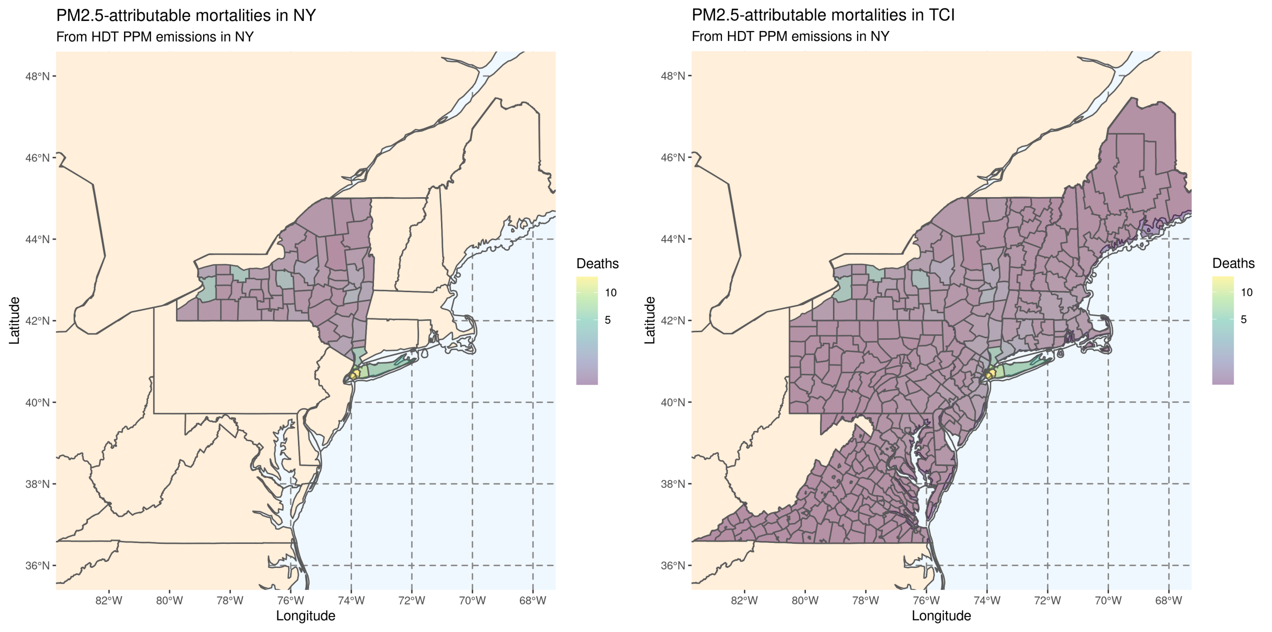





$PM_{2.5}$ sensitivities to HDT PPM emissions from NY



$PM_{2.5}$-attributable premature mortalities within the state and across the entire TCI region due to NY HDT PPM




**This is an instance of air quality/health impacts remaining localized to the source region**

HDT, Heavy Duty Trucks; $PM_{2.5}$, Fine Particulate Matter with aerodynamic diameter <2.5 microns; PPM, Primary Particulate Matter; TCI, Transportation Climate Initiative.

# Population-Weighted Exposure and Health Outcomes

| | $PM_{2.5}$ ($\mu g/m^3$) | | | | | $O_3$ (ppb) | |
|---|---|---|---|---|---|---|---|
| | $NO_X$ | VOC | $NH_3$ | $SO_2$ | PPM | $NO_X$ | VOC |
| LDA | 6.2E-04 | 1.7E-03 | 3.7E-03 | 1.7E-04 | 5.8E-03 | 3.3E-02 | 1.5E-02 |
| LDT | 1.4E-03 | 1.9E-03 | 3.3E-03 | 1.9E-04 | 6.0E-03 | 6.3E-02 | 1.6E-02 |
| MDT | 3.8E-04 | 2.4E-04 | 2.6E-04 | 1.5E-05 | 5.5E-03 | 2.2E-02 | 2.6E-03 |
| HDT | 9.3E-04 | 1.3E-04 | 3.1E-04 | 1.9E-05 | 7.2E-03 | 4.0E-02 | 1.4E-03 |
| BUS | 5.8E-05 | 6.0E-05 | 5.7E-05 | 3.2E-06 | 2.1E-03 | 4.7E-03 | 7.2E-04 |

$PM_{2.5}$ population weighted sensitivities to PPM are the largest for all vehicles across the TCI region

Population weighted sensitivities to $NH_3$ are close in magnitude to PPM for light duty vehicles

$O_3$ population weighted sensitivities to $NO_X$ are larger than sensitivities to VOC

# Population-Weighted Exposure and Health Outcomes

| | $PM_{2.5}$ ($\mu g/m^3$) | | | | | $O_3$ (ppb) | |
|---|---|---|---|---|---|---|---|
| | $NO_X$ | VOC | $NH_3$ | $SO_2$ | PPM | $NO_X$ | VOC |
| LDA | 6.2E-04 | 1.7E-03 | 3.7E-03 | 1.7E-04 | 5.8E-03 | 3.3E-02 | 1.5E-02 |
| LDT | 1.4E-03 | 1.9E-03 | 3.3E-03 | 1.9E-04 | 6.0E-03 | 6.3E-02 | 1.6E-02 |
| MDT | 3.8E-04 | 2.4E-04 | 2.6E-04 | 1.5E-05 | 5.5E-03 | 2.2E-02 | 2.6E-03 |
| HDT | 9.3E-04 | 1.3E-04 | 3.1E-04 | 1.9E-05 | 7.2E-03 | 4.0E-02 | 1.4E-03 |
| BUS | 5.8E-05 | 6.0E-05 | 5.7E-05 | 3.2E-06 | 2.1E-03 | 4.7E-03 | 7.2E-04 |

| | | Percentage of deaths from precursor (%) | | | | |
|---|---|---|---|---|---|---|
| | Mortalities | $NO_X$ | VOC | $NH_3$ | $SO_2$ | PPM |
| LDA | 1153 (974 – 1341) | 5 | 14 | 31 | 1 | 47 |
| LDT | 1234 (1042 – 1434) | 12 | 15 | 26 | 1 | 46 |
| MDT | 601 (507 – 698) | 6 | 4 | 4 | 0 | 85 |
| HDT | 829 (701 – 964) | 11 | 1 | 4 | 0 | 83 |
| BUS | 206 (174 – 240) | 3 | 3 | 3 | 0 | 91 |

Percentage of premature mortalities from each precursor follows similar trends to magnitudes of population weighted exposures

# Population-Weighted Exposure and Health Outcomes

| | $PM_{2.5}$ (μg/m³) | | | | | $O_3$ (ppb) | |
|---|---|---|---|---|---|---|---|
| | $NO_X$ | VOC | $NH_3$ | $SO_2$ | PPM | $NO_X$ | VOC |
| LDA | 6.2E-04 | 1.7E-03 | 3.7E-03 | 1.7E-04 | 5.8E-03 | 3.3E-02 | 1.5E-02 |
| LDT | 1.4E-03 | 1.9E-03 | 3.3E-03 | 1.9E-04 | 6.0E-03 | 6.3E-02 | 1.6E-02 |
| MDT | 3.8E-04 | 2.4E-04 | 2.6E-04 | 1.5E-05 | 5.5E-03 | 2.2E-02 | 2.6E-03 |
| HDT | 9.3E-04 | 1.3E-04 | 3.1E-04 | 1.9E-05 | 7.2E-03 | 4.0E-02 | 1.4E-03 |
| BUS | 5.8E-05 | 6.0E-05 | 5.7E-05 | 3.2E-06 | 2.1E-03 | 4.7E-03 | 7.2E-04 |

| | | Percentage of deaths from precursor (%) | | | | |
|---|---|---|---|---|---|---|
| | Mortalities | $NO_X$ | VOC | $NH_3$ | $SO_2$ | PPM |
| LDA | 1153 (974 – 1341) | 5 | 14 | 31 | 1 | 47 |
| LDT | 1234 (1042 – 1434) | 12 | 15 | 26 | 1 | 46 |
| MDT | 601 (507 – 698) | 6 | 4 | 4 | 0 | 85 |
| HDT | 829 (701 – 964) | 11 | 1 | 4 | 0 | 83 |
| BUS | 206 (174 – 240) | 3 | 3 | 3 | 0 | 91 |

| | | Percentage of deaths from precursor (%) | |
|---|---|---|---|
| | Mortalities | $NO_X$ | VOC |
| LDA | 728 (364 – 1456) | 69 | 31 |
| LDT | 1229 (615 – 2459) | 80 | 20 |
| MDT | 395 (197 – 790) | 90 | 10 |
| HDT | 636 (318 – 1272) | 97 | 3 |
| BUS | 91 (45 – 181) | 88 | 12 |

$O_3$-attributable mortalities are less than $PM_{2.5}$

# Source-Receptor Health Outcomes

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$O_3$

| | Source | Receptor: BALMSA | BOSMSA | CT | DC | DE | MA | MD | ME | NH | NJ | NY | NYMSA | PA | PHILMSA | RI | VA | VT |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| LDA | BALMSA | **38.3** | 3.5 | 2.9 | 2.0 | **3.9** | 5.5 | **31.3** | 0.3 | 0.7 | 15.1 | 17.3 | 22.8 | 27.2 | 19.9 | 1.3 | 14.8 | 0.2 |
| | BOSMSA | 0.1 | 4.1 | 1.3 | 0.0 | 0.1 | 5.7 | 0.1 | 2.0 | 1.3 | 1.8 | 3.0 | 3.9 | 1.2 | 1.0 | 1.2 | 0.1 | 0.1 |
| | CT | 0.2 | 4.5 | 9.1 | 0.0 | 0.3 | 8.4 | 0.3 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 0.2 | 0.1 |
| | DC | 1.4 | 0.3 | 0.3 | -1.9 | 0.3 | 0.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 0.9 | 0.0 |
| | DE | 1.8 | 0.9 | 1.0 | 0.2 | 0.8 | 1.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1.0 | 0.0 |
| | MA | 0.1 | 9.2 | 3.3 | 0.0 | 0.2 | 13.4 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 0.2 | 0.2 |
| | MD | 22.4 | 2.7 | 2.1 | 1.9 | 3.3 | 4.2 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 6.6 | 0.2 |
| | ME | 0.1 | 1.6 | 0.4 | 0.0 | 0.0 | 1.9 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 0.1 | 0.1 |
| | NH | 0.1 | 3.6 | 0.4 | 0.0 | 0.0 | 3.9 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 0.0 | 0.1 |
| | NJ | 2.6 | 4.6 | 7.9 | 0.2 | 1.3 | 7.6 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1.4 | 0.2 |
| | NY | 3.5 | **9.3** | 17.5 | 0.3 | 1.3 | **16.8** | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1.9 | **1.2** |
| | NYMSA | 2.4 | 8.4 | **18.7** | 0.2 | 1.5 | 14.6 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1.6 | 0.3 |
| | PA | 14.0 | 4.7 | 6.4 | 1.1 | 3.6 | 7.7 | 12.6 | 0.9 | 1.3 | **37.7** | 38.5 | 56.8 | **55.0** | **32.0** | 1.4 | 6.2 | 0.6 |
| | PHILMSA | 3.9 | 2.3 | 2.6 | 0.3 | 1.6 | 3.5 | 3.8 | 0.4 | 0.4 | 24.1 | 17.0 | 30.3 | 15.7 | 19.3 | 0.8 | 1.9 | 0.1 |
| | RI | 0.0 | 2.7 | 0.5 | 0.0 | 0.0 | 4.1 | 0.0 | 0.3 | 0.2 | 0.8 | 1.7 | 2.2 | 0.4 | 0.3 | 0.0 | 0.0 | 0.0 |
| | VA | 31.7 | 3.0 | 2.7 | **4.4** | 2.4 | 5.1 | 20.8 | 0.3 | 0.5 | 11.0 | 13.8 | 17.1 | 16.5 | 10.8 | 1.3 | **32.3** | 0.2 |
| | VT | 0.1 | 1.1 | 0.3 | 0.0 | 0.0 | 1.5 | 0.0 | 0.3 | 0.6 | 0.4 | 1.1 | 1.0 | 0.3 | 0.1 | 0.2 | 0.0 | 0.4 |

The largest contributor to $O_3$-attributable premature mortalities in MA is NY, when considering emissions from LDA

# Source-Receptor Health Outcomes

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$O_3$

| | Source | Receptor | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | BALMSA | BOSMSA | CT | DC | DE | MA | MD | ME | NH | NJ | NY | NYMSA | PA | PHILMSA | RI | VA | VT |
| LDA | BALMSA | **38.3** | 3.5 | 2.9 | 2.0 | **3.9** | 5.5 | **31.3** | 0.3 | 0.7 | 15.1 | 17.3 | 22.8 | 27.2 | 19.9 | 1.3 | 14.8 | 0.2 |
| | BOSMSA | 0.1 | 4.1 | 1.3 | 0.0 | 0.1 | 5.7 | 0.1 | 2.0 | 1.3 | 1.8 | 3.0 | 3.9 | 1.2 | 1.0 | 1.2 | 0.1 | 0.1 |
| | CT | 0.2 | 4.5 | 9.1 | 0.0 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1.7 | 2.3 | 0.2 | 0.1 |
| | DC | 1.4 | 0.3 | 0.3 | -1.9 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1.7 | 0.1 | 0.9 | 0.0 |
| | DE | 1.8 | 0.9 | 1.0 | 0.2 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 7.5 | 0.4 | 1.0 | 0.0 |
| | MA | 0.1 | 9.2 | 3.3 | 0.0 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1.7 | 2.6 | 0.2 | 0.2 |
| | MD | 22.4 | 2.7 | 2.1 | 1.9 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 15.2 | 1.0 | 6.6 | 0.2 |
| | ME | 0.1 | 1.6 | 0.4 | 0.0 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 0.2 | 0.3 | 0.1 | 0.1 |
| | NH | 0.1 | 3.6 | 0.4 | 0.0 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 0.2 | 0.3 | 0.0 | 0.1 |
| | NJ | 2.6 | 4.6 | 7.9 | 0.2 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 11.1 | 1.8 | 1.4 | 0.2 |
| | NY | 3.5 | **9.3** | 17.5 | 0.3 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 9.3 | 3.4 | 1.9 | **1.2** |
| | NYMSA | 2.4 | 8.4 | **18.7** | 0.2 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 10.8 | **3.5** | 1.6 | 0.3 |
| | PA | 14.0 | 4.7 | 6.4 | 1.1 | 3.6 | 7.7 | 12.6 | 0.9 | 1.3 | **37.7** | 38.5 | 56.8 | **55.0** | **32.0** | 1.4 | 6.2 | 0.6 |
| | PHILMSA | 3.9 | 2.3 | 2.6 | 0.3 | 1.6 | 3.5 | 3.8 | 0.4 | 0.4 | 24.1 | 17.0 | 30.3 | 15.7 | 19.3 | 0.8 | 1.9 | 0.1 |
| | RI | 0.0 | 2.7 | 0.5 | 0.0 | 0.0 | 4.1 | 0.0 | 0.3 | 0.2 | 0.8 | 1.7 | 2.2 | 0.4 | 0.3 | 0.0 | 0.0 | 0.0 |
| | VA | 31.7 | 3.0 | 2.7 | **4.4** | 2.4 | 5.1 | 20.8 | 0.3 | 0.5 | 11.0 | 13.8 | 17.1 | 16.5 | 10.8 | 1.3 | **32.3** | 0.2 |
| | VT | 0.1 | 1.1 | 0.3 | 0.0 | 0.0 | 1.5 | 0.0 | 0.3 | 0.6 | 0.4 | 1.1 | 1.0 | 0.3 | 0.1 | 0.2 | 0.0 | 0.4 |

The largest contributor to $O_3$-attributable premature mortalities in VA is VA, when considering emissions from LDA

# Source-Receptor Health Outcomes

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## $O_3$

| | Source | BALMSA | BOSMSA | CT | DC | DE | MA | MD | ME | NH | NJ | NY | NYMSA | PA | PHILMSA | RI | VA | VT |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Receptor | | | | | | | | | | | | | | | | |
| | BALMSA | **38.3** | 3.5 | 2.9 | 2.0 | **3.9** | 5.5 | **31.3** | 0.3 | 0.7 | 15.1 | 17.3 | 22.8 | 27.2 | 19.9 | 1.3 | 14.8 | 0.2 |
| | BOSMSA | 0.1 | 4.1 | 1.3 | 0.0 | 0.1 | 5.7 | 0.1 | 2.0 | 1.3 | 1.8 | 3.0 | 3.9 | 1.2 | 1.0 | 1.2 | 0.1 | 0.1 |
| | CT | 0.2 | 4.5 | 9.1 | 0.0 | 0.3 | 8.4 | 0.3 | 0.4 | 0.7 | 4.4 | 13.2 | 15.7 | 1.6 | 1.7 | 2.3 | 0.2 | 0.1 |
| | DC | 1.4 | 0.3 | 0.3 | -1.9 | 0.3 | 0.5 | 3.4 | 0.0 | 0.1 | 1.4 | 1.7 | 2.2 | 2.2 | 1.7 | 0.1 | 0.9 | 0.0 |
| | DE | 1.8 | 0.9 | 1.0 | 0.2 | 0.8 | 1.5 | 1.7 | 0.1 | 0.1 | 5.9 | 4.6 | 6.9 | 6.3 | 7.5 | 0.4 | 1.0 | 0.0 |
| | MA | 0.1 | 9.2 | 3.3 | 0.0 | 0.2 | 13.4 | 0.2 | **2.3** | 1.8 | 3.3 | 5.5 | 7.3 | 2.0 | 1.7 | 2.6 | 0.2 | 0.2 |
| | MD | 22.4 | 2.7 | 2.1 | 1.9 | 3.3 | 4.2 | 20.0 | 0.2 | 0.5 | 11.0 | 11.9 | 16.2 | 20.3 | 15.2 | 1.0 | 6.6 | 0.2 |
| | ME | 0.1 | 1.6 | 0.4 | 0.0 | 0.0 | 1.9 | 0.1 | 1.8 | 0.6 | 0.5 | 1.1 | 1.2 | 0.4 | 0.2 | 0.3 | 0.1 | 0.1 |
| LDA | NH | 0.1 | 3.6 | 0.4 | 0.0 | 0.0 | 3.9 | 0.1 | 0.9 | 1.3 | 0.5 | 1.0 | 1.2 | 0.3 | 0.2 | 0.3 | 0.0 | 0.1 |
| | NJ | 2.6 | 4.6 | 7.9 | 0.2 | 1.3 | 7.6 | 2.7 | 0.6 | 0.7 | 24.6 | **51.3** | **67.9** | 9.0 | 11.1 | 1.8 | 1.4 | 0.2 |
| | NY | 3.5 | **9.3** | 17.5 | 0.3 | 1.3 | **16.8** | 3.3 | 1.6 | **2.1** | 19.7 | 31.6 | 32.8 | 12.9 | 9.3 | 3.4 | 1.9 | **1.2** |
| | NYMSA | 2.4 | 8.4 | **18.7** | 0.2 | 1.5 | 14.6 | 2.7 | 1.2 | 1.2 | 25.3 | 36.2 | 52.9 | 9.5 | 10.8 | **3.5** | 1.6 | 0.3 |
| | PA | 14.0 | 4.7 | 6.4 | 1.1 | 3.6 | 7.7 | 12.6 | 0.9 | 1.3 | **37.7** | 38.5 | 56.8 | **55.0** | **32.0** | 1.4 | 6.2 | 0.6 |
| | PHILMSA | 3.9 | 2.3 | 2.6 | 0.3 | 1.6 | 3.5 | 3.8 | 0.4 | 0.4 | 24.1 | 17.0 | 30.3 | 15.7 | 19.3 | 0.8 | 1.9 | 0.1 |
| | RI | 0.0 | 2.7 | 0.5 | 0.0 | 0.0 | 4.1 | 0.0 | 0.3 | 0.2 | 0.8 | 1.7 | 2.2 | 0.4 | 0.3 | 0.0 | 0.0 | 0.0 |
| | VA | 31.7 | 3.0 | 2.7 | **4.4** | 2.4 | 5.1 | 20.8 | 0.3 | 0.5 | 11.0 | 13.8 | 17.1 | 16.5 | 10.8 | 1.3 | **32.3** | 0.2 |
| | VT | 0.1 | 1.1 | 0.3 | 0.0 | 0.0 | 1.5 | 0.0 | 0.3 | 0.6 | 0.4 | 1.1 | 1.0 | 0.3 | 0.1 | 0.2 | 0.0 | 0.4 |

## $PM_{2.5}$

| | Source | BALMSA | BOSMSA | CT | DC | DE | MA | MD | ME | NH | NJ | NY | NYMSA | PA | PHILMSA | RI | VA | VT |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Receptor | | | | | | | | | | | | | | | | |
| | BA | | | | | | | | | 0.2 | 12.4 | 14.9 | 20.5 | 29.0 | 15.9 | 0.4 | 30.4 | 0.1 |
| | B | | | | | | | | | 2.2 | 1.4 | 2.4 | 3.0 | 1.3 | 1.1 | 1.5 | 0.3 | 0.1 |
| | | | | | | | | | | 0.6 | 2.0 | 6.6 | 7.6 | 1.4 | 1.0 | 1.5 | 0.4 | 0.1 |
| | | | | | | | | | | 0.0 | 1.2 | 1.1 | 1.6 | 2.8 | 1.8 | 0.0 | 3.3 | 0.0 |
| | | | | | | | | | | 0.0 | 3.6 | 3.0 | 4.5 | 4.5 | 8.5 | 0.1 | 0.7 | 0.0 |
| | | | | | | | | | | 1.5 | 2.2 | 4.0 | 4.9 | 1.9 | 1.6 | 3.2 | 0.4 | 0.1 |
| | | | | | | | | | | 0.1 | 9.8 | 11.4 | 16.1 | 20.1 | 12.7 | 0.3 | 9.2 | 0.1 |
| | | | | | | | | | | 0.4 | 0.1 | 0.3 | 0.4 | 0.1 | 0.1 | 0.1 | 0.0 | 0.0 |
| LDA | NH | 0.2 | 4.0 | 0.4 | 0.0 | 0.0 | 3.5 | 0.1 | 0.5 | **3.3** | 0.4 | 0.8 | 1.0 | 0.3 | 0.3 | 0.3 | 0.1 | 0.1 |
| | NJ | 3.7 | 2.3 | 5.7 | 0.4 | 1.2 | 4.1 | 3.1 | 0.4 | 0.4 | 113.0 | 72.3 | 165.0 | 13.0 | 21.8 | 0.8 | 2.6 | 0.1 |
| | NY | 3.6 | 6.6 | 14.2 | 0.4 | 0.7 | 11.1 | 2.8 | 1.0 | 1.4 | 19.6 | 216.0 | 199.0 | 8.6 | 6.0 | 2.1 | 2.3 | 0.7 |
| | NYMSA | 4.8 | 4.8 | 15.7 | 0.6 | 1.1 | 8.7 | 3.8 | 0.8 | 0.9 | **105.0** | **238.0** | **335.0** | 8.9 | 8.1 | 2.0 | 3.2 | 0.3 |
| | PA | 16.1 | 2.9 | 5.3 | 1.6 | 4.1 | 4.9 | 13.6 | 0.4 | 0.5 | 33.5 | 34.5 | 47.9 | **131.0** | 75.8 | 1.1 | 5.9 | 0.3 |
| | PHILMSA | 3.9 | 1.1 | 2.2 | 0.4 | **6.0** | 1.8 | 3.8 | 0.2 | 0.2 | 29.9 | 14.6 | 23.8 | 59.4 | **76.6** | 0.4 | 2.3 | 0.1 |
| | RI | 0.1 | 1.7 | 0.5 | 0.0 | 0.0 | 3.1 | 0.1 | 0.2 | 0.1 | 0.4 | 0.6 | 0.8 | 0.2 | 0.1 | **6.7** | 0.1 | 0.0 |
| | VA | 37.7 | 0.9 | 1.2 | 5.3 | 1.0 | 1.6 | 15.4 | 0.1 | 0.2 | 5.8 | 8.6 | 10.5 | 15.3 | 7.3 | 0.4 | **49.9** | 0.1 |
| | VT | 0.1 | 0.6 | 0.2 | 0.0 | 0.0 | 0.8 | 0.0 | 0.1 | 0.3 | 0.2 | 0.5 | 0.4 | 0.1 | 0.1 | 0.1 | 0.0 | **0.8** |

The largest contributor to $PM_{2.5}$ – attributable premature mortalities in NJ, NY, and NYMSA is NYMSA, when considering emissions from LDA

# Damages per ton emitted precursor

For each receptor region, we can determine the largest damages/ton emitted from a given source region/vehicle class/precursor

Total damages are the sum of both $PM_{2.5}$ and $O_3$ mortalities

In each receptor region, only PPM and $NH_3$ are in the top 10 damages/ton

Depending on the receptor region, top damages/ton sources can come from the region itself or another source region

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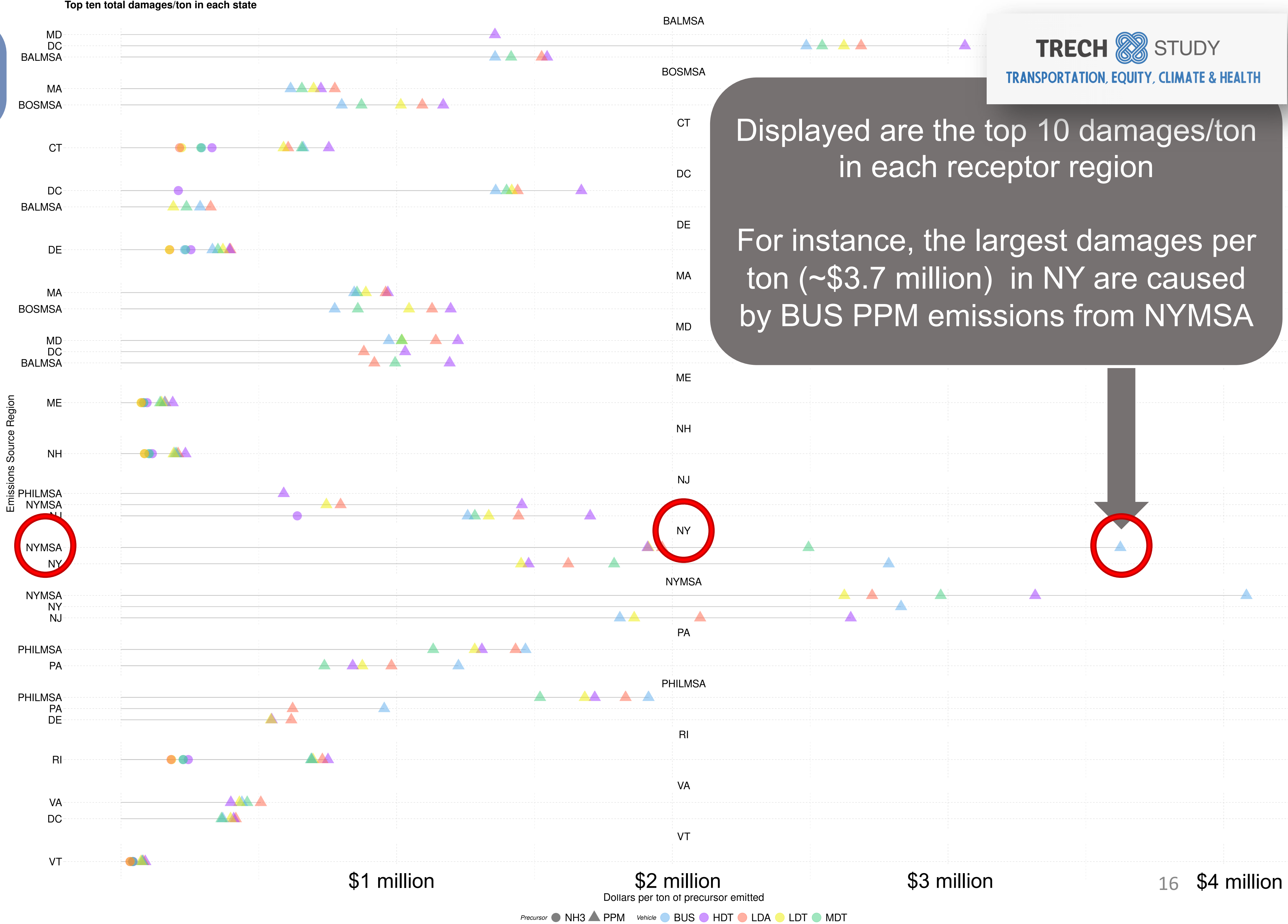
Displayed are the top 10 damages/ton in each receptor region

For instance, the largest damages per ton (~$3.7 million) in NY are caused by BUS PPM emissions from NYMSA



# Summary

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- For each state in the TCI region we are able to determine the largest source region/vehicle class/precursor contributor to $PM_{2.5}$ and $O_3$ -attributable premature mortalities in the state on an absolute basis as well as a per ton emitted precursor basis
- This information can be used to guide policies specific to reducing on-road vehicles' impact in individual states across the TCI region
- Sensitivities allow us to calculate pollution concentration changes across the TCI region and in each individual state due to changes in source region/vehicle class/precursor emissions

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