Supplementary Information

Environmental health, racial/ethnic health-disparity, and climate impacts of inter-regional freight transport in the United States

Maninder P. S. Thind*, Christopher W. Tessum, and Julian D. Marshall*

No. of pages = 25

No. of figures = 23

No. of tables = 10

*Corresponding author:

Julian Marshall: jdmarsh@uw.edu

Maninder Thind: thind@uw.edu

Additional Methods

Majority (about two-thirds of the tonnage) of the freight data in FAF comes from the Commodity Flow Survey (CFS) and remaining is estimated based on multiple, publicly available data sources. To locate the specific point within FAF region at origin and destination, we use the locations of the intermodal freight facilities by mode (airports, ports, railway stations, truck stops/terminals) from the NTAD dataset[1] (***Figure S5***) and urban areas[2] within the FAF regions. The origin and destination point is the closest freight facility to the centroid of urban areas within a FAF region.

Truck emission factors (EFs) in GREET model are originally estimated using data from U.S EPA's Motor Vehicle Emission Simulator (MOVES) model. Truck EFs are average of all emission processes during vehicle operation (e.g., running and start exhaust, crankcase emissions, tire-wear) and road conditions (rural, urban). As a sensitivity analysis, for routes < 200 miles, we use GREET EFs for combination short-haul HDT (see ***Table S3***Error! Reference source not found.). Rail and barge EFs in GREET model are based on data from different sources including data by Association of American Railroads for rail and US EPA and ICF Consulting for marine engines (barge).

Aircraft is categorized into four classes based on US DOT John A. Volpe National Transportation Systems Center's Aviation Environmental Design Tool (AEDT) tool:[3] Single Aisle (SA), Small Twin Aisle (STA), Large Twin Aisle (LTA), and Large Quad (LQ), which are categorized by average payload and average flight distance (***Table S4***).

Emissions (kg per megatonne) = $\mathrm{EF}\ \left(\frac{\mathrm{kg}}{\mathrm{megatonne-mile}}\right) \times \text{Length of intersected segment (mile)}$
(1)

Aircraft cruise emissions (height = 11 km) are allocated to great circle route by intersecting with topmost InMAP layer (at lowest resolution of 48 × 48 km) and using equation (1). LTO emissions are allocated to each phase of LTO cycle separately: idle/taxi-in, idle-out, and take-off emissions allocated to runway (ground-level, height = 0), approach emissions allocated to approach slope, and climb-out emissions allocated to climb-out slope. Approach and climb-out emissions are distributed equally for each 1 km segment along the slopes at the height equal to midpoint of each segment (***Figure S7***). Truck, rail, and barge are modeled as ground-level sources (height = 0).

Number of premature deaths = $\left(e^{(\beta\times[PM_{2.5}])} - 1\right) \times P \times \frac{\text{All-Cause mortality rate}}{100{,}000}$ *(2)*

Here, β is $PM_{2.5}$ linear coefficient = ln(1.078)/10 = 0.00751, i.e., a 7.8% increase in the number of premature deaths for every 10 μg/m³ increase in the concentration of $PM_{2.5}$. $[PM_{2.5}]$ is the concentration of $PM_{2.5}$. P is total population.

The ratio of total FAF tonne-kms to the calculated tonne-kms varies by each O-D pair with a median (IQR) of ~1.0 (minimum and maximum values of ratio in ***Table S7***) for each mode.

Population-weighted concentrations are calculated as follows:

$$\text{population weighted average } PM_{2.5} \text{ concentration} = \frac{\sum_{i=1}^{n} (P_i \times [PM_{2.5}]_i)}{\sum_{i=1}^{n} P_i} \quad (3)$$

Here, P_i is the number of people in grid cell i, $[PM_{2.5}]_i$ is concentration in grid cell i, and n is total number of grid cells.

VSL used in this work is based on $8.3 million per death from Goodkind et al. (2019),[4] then inflation adjusted to year-2020 using US Bureau of Labor Statistics's CPI inflation calculator.[5]

Additional Results and Discussion

Aircraft LTO impacts are estimated as average of two orientations (original and reversed). The average of absolute difference between reversed and original orientation among all O-D pairs is 0.04 deaths per megaton (or 4% relative to original). Range of differences between two orientations is -0.15 to 0.17 deaths per megaton (or -22% to 31% relative to original).

The actual slopes are a function of many factors including obstacles, meteorology, and surface conditions. Approach slope typically varies between 2.6° to a maximum of 3.7°. Climb-out angle (or "angle of attack") can vary considerably during first 3000 ft climb, where it can be two to three times larger than the slope assumed in this work. We perform a sensitivity analysis to investigate how much impacts change with increase in approach slope from 2.6° to 3.7° and climb-out slope from 2° to 10°. This sensitivity analysis assumes that approach and climb-out emission factors for minimum slopes are allocated to all other slopes at the increment of 1° as well. That is, two factors change in the new angles: (1) increased emissions in smaller slope segments but (2) at a greater height. We find **(*Figure*** *S22*that deaths per megatonne do not vary significantly with angle of attack. As the angle increases, impact decreases, reflecting that the climb-out becomes shorter and so there are fewer total people directly under the climb-out segment. Absolute difference between approach angles is also small, under 5%. However, as noted above, our sensitivity analysis is based on conservative assumptions. Using data from Turkish airlines, Turgut et al. (2019) indicates that fuel flow is a strong linear function of approach angle up to 2.5°-3° and the effect diminishes after 3°.[6] For climb angle, Turgut et al. (2018) shows that fuel burn and NO_x emissions tend to increase by 9–19 kg and 0.3–0.7 kg per degree of climb angle for the departure climb phase. Though these numbers are also likely to have minor impact on our results.

The US DOT's FAF data projects that freight tonne-kms will increase by 48% (truck), 9% (rail), 19% (water), and 110% (air) by 2045 from 2017.[7] Large retailers such as Amazon will need to optimize time and transit by different modes (e.g., truck, aircraft) to meet customer demands such as rush shipping, which can have direct impact on the environment.[8] Our results can be useful to e-commerce companies and retailers to provide customers with options to choose method of delivery (e.g., rush vs green shipping) based on health, climate, and exposure disparity metrics of different transportation modes. The comparison between modes can be useful for their transportation strategies to meet the environmental goals of the company.

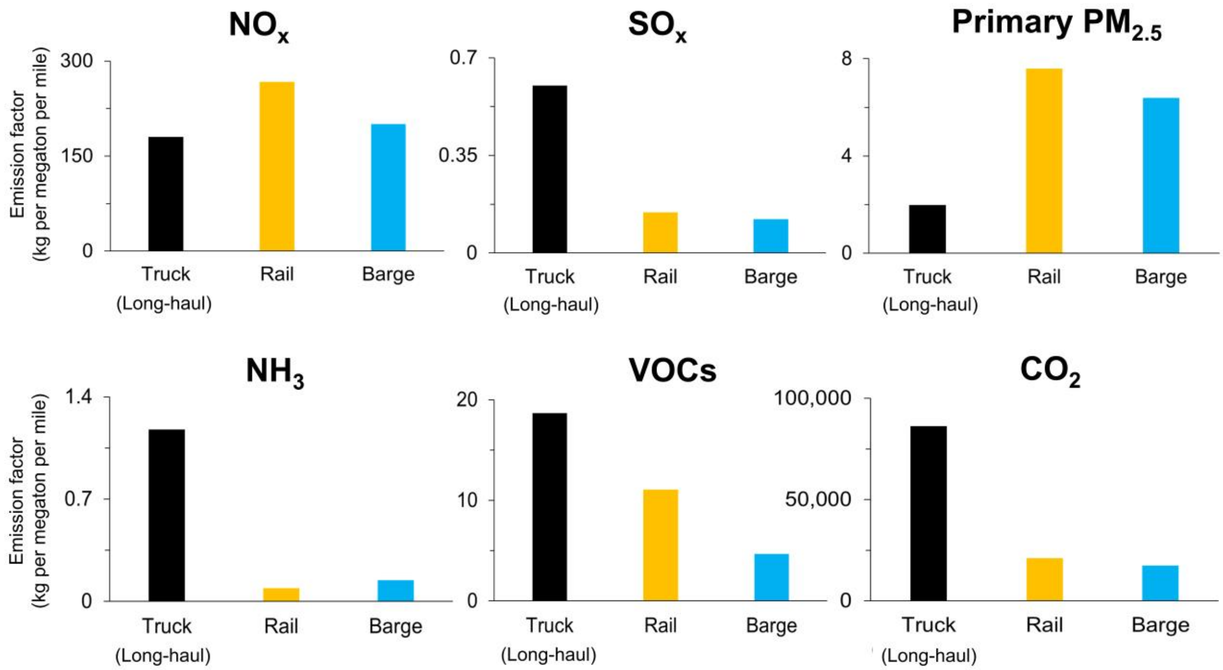

Figure S1. Emission factors for non-aircraft modes by pollutant.

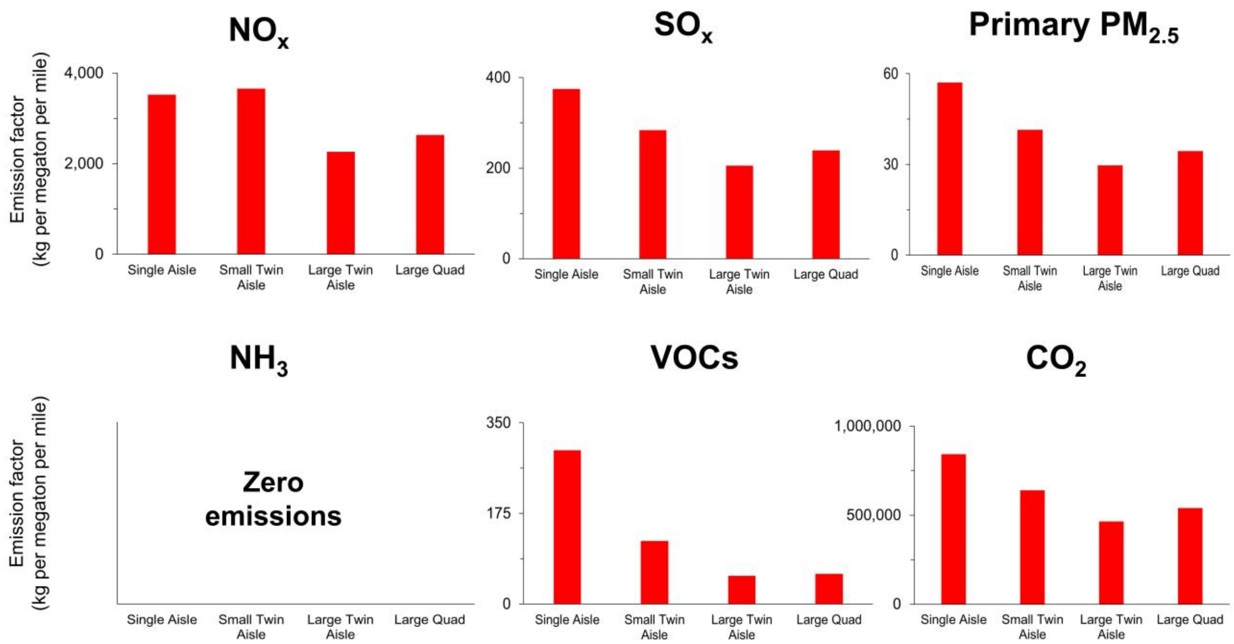

Figure S2. Cruise emission factors for an aircraft in kg per megaton payload per mile of great circle distance.

Table S1. Landing and take-off (LTO) cycle emission factors by aircraft type for five stages: take-off, climb-out, approach, Idle/Taxi-in, and Idle/Taxi-out

Pollutant	LTO stage	EF Single Aisle (kg/megaton)	EF Small Twin Aisle (kg/megaton)	EF Large Twin Aisle (kg/megaton)	EF Large Quad (kg/megaton)
CO_2	Take-off	9,698,826	7,209,271	5,697,412	7,782,233
	Climb-out	24,802,095	18,435,738	14,569,573	19,900,931
	Approach	14,827,780	11,021,693	8,710,330	11,897,649
	Idle/Taxi-in	8,532,050	6,341,990	5,012,009	6,846,024
	Idle/Taxi-out	23,165,367	17,219,136	13,608,105	18,587,638
VOCs	Take-off	6,282	4,998	3,346	4,387
	Climb-out	16,064	12,780	8,557	11,217
	Approach	9,604	7,640	5,115	6,706
	Idle/Taxi-in	5,526	4,396	2,943	3,859
	Idle/Taxi-out	15,004	11,936	7,992	10,477
NO_x	Take-off	37,478	41,272	39,759	54,340
	Climb-out	95,841	105,542	101,672	138,959
	Approach	57,298	63,098	60,784	83,076
	Idle/Taxi-in	32,970	36,307	34,976	47,803
	Idle/Taxi-out	89,516	98,577	94,963	129,789
Primary $PM_{2.5}$	Take-off	190	90	85	88
	Climb-out	486	229	217	224
	Approach	291	137	130	134
	Idle/Taxi-in	167	79	75	77
	Idle/Taxi-out	454	214	203	209
SO_x	Take-off	4,325	3,216	2,539	3,465
	Climb-out	11,059	8,223	6,492	8,860
	Approach	6,612	4,916	3,881	5,297
	Idle/Taxi-in	3,804	2,829	2,233	3,048
	Idle/Taxi-out	10,329	7,681	6,064	8,275

Data source: Derived from GREET Model (version 2020) and International Civil Aviation Organization (ICAO)'s database

Table S2. Ratio of emission factors for ultra-low sulfur jet fuel (ULSJ) (sulfur content = 11 ppm) to the conventional jet fuel (Sulfur content=700 ppm)

Pollutant	Ratio Single Aisle	Ratio Small Twin Aisle	Ratio Large Twin Aisle	Ratio Large Quad
CO_2	1	1	1	1
VOC	1	1	1	1
NO_x	1	1	1	1
Primary $PM_{2.5}$	1.8	2.7	2.2	2.8

SO_x	0.016	0.016	0.016	0.016

Table S3. Emission factors (EFs) for combination short-haul heavy-duty truck

Pollutant	EF (kg per megaton per mile) for combination short-haul heavy-duty truck
NO_x	67.6
SO_x	0.64
$PM_{2.5}$	1.4
NH_3	0.94
VOC	2.7
CO_2	92,680

Table S4. 2010 US origin only Aviation Environmental Design Tool (AEDT) aircraft types and operational performance data from US DOT's John A. Volpe National Transportation Systems Center

Aircraft class	Average payload (kg/operation)	Average trip great circle distance (km/operation)	As-operated aircraft average trip petroleum jet fuel consumption (kg/operation)	Aircraft LTO cycle average petroleum jet fuel consumption (kg/operation)
Single Aisle (SA)	21,036	723	3,389	598
Small Twin Aisle (STA)	44,848	1,415	9,769	949
Large Twin Aisle (LTA)	89,596	3,317	31,414	1,496
Large Quad (LQ)	99,663	5,019	60,771	2,271

Data Source: GREET Model (version 2020)

Table S5. Reference LTO cycle from ICAO's Airport Air Quality Manual

Operating phase	Time in mode (minutes)
Take-off	0.7
Climb-out	2.2
Approach	4
Idle In	7
Idle Out	19

Figure S3. 132 Freight Analysis Framework (FAF) regions. Map based on GIS files from the U.S. DOT's National Transportation Atlas Database (NTAD).

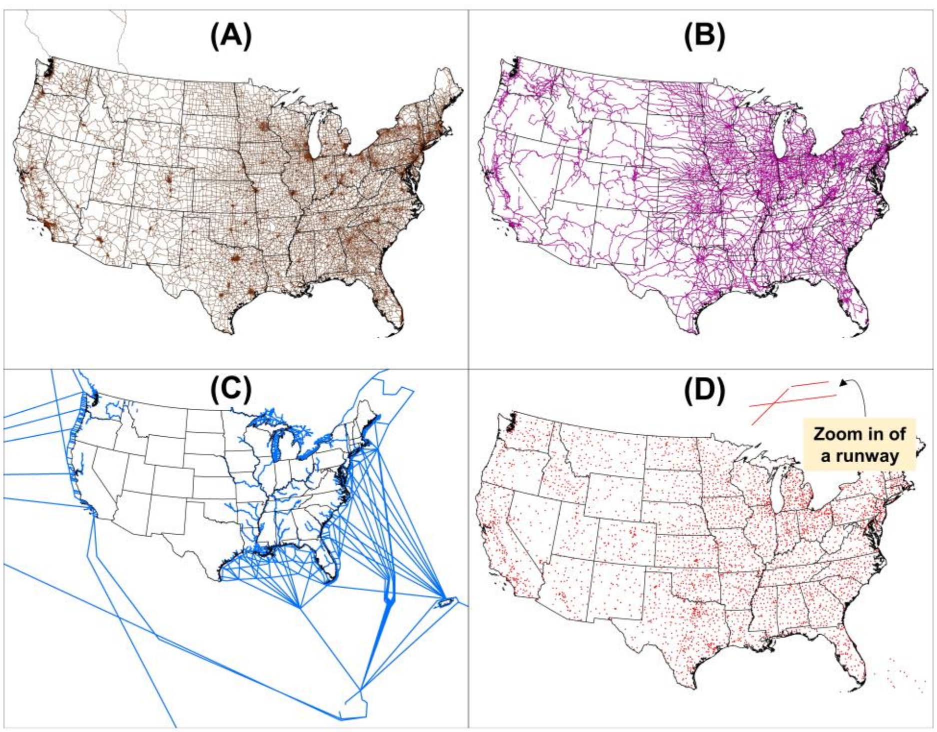

Figure S4. (A) Road network: Primary & Secondary roads, highways; (B) Rail lines network; (C) Navigable waterway lines; and (D) Runways. Maps based on GIS files from the U.S. DOT's National Transportation Atlas Database (NTAD).

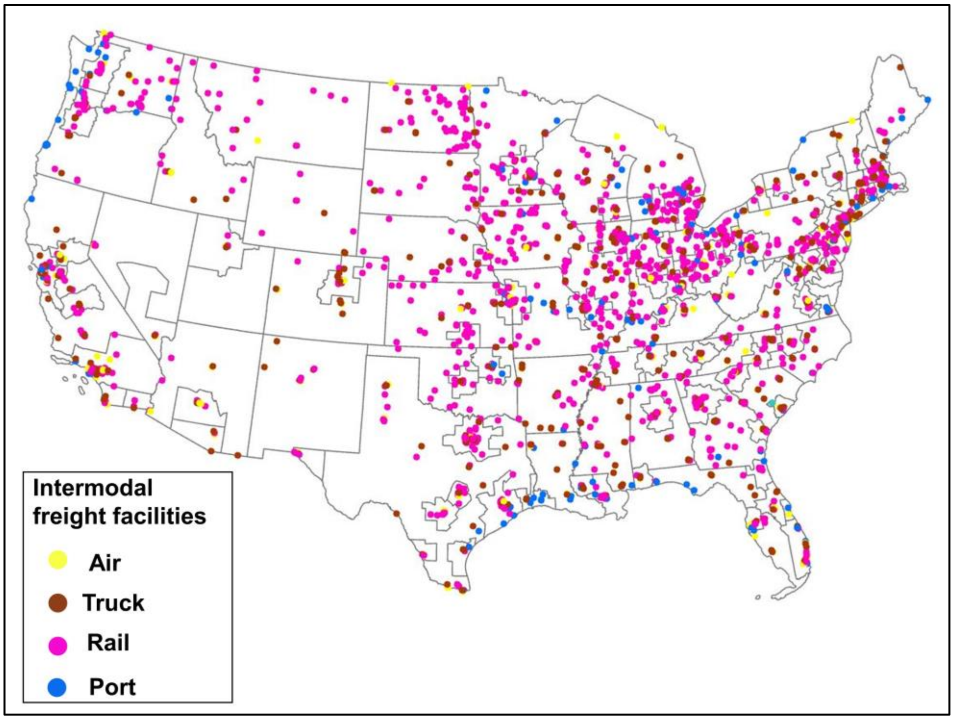

Figure S5. Intermodal freight facilities (some facilities overlap in this map). Map based on GIS files from the U.S. DOT's National Transportation Atlas Database (NTAD).

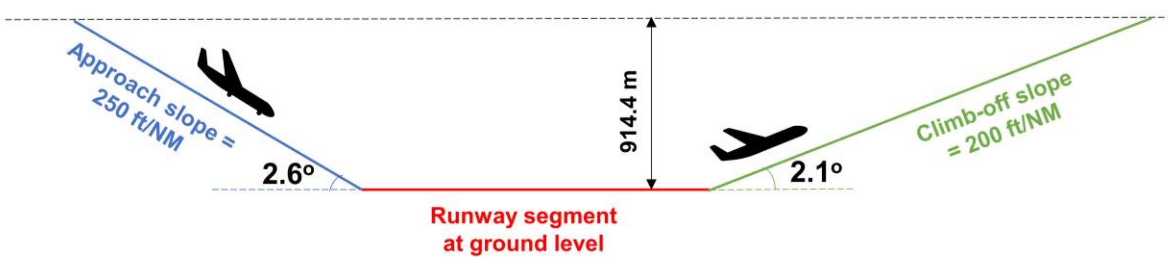

Figure S6. Side projection of simplified Landing and Take-off cycle (LTO).

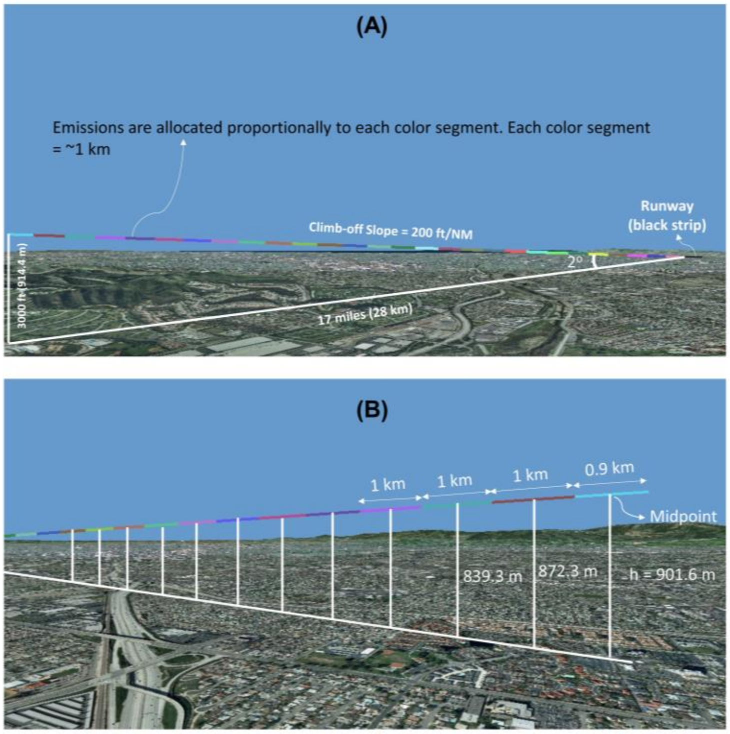

Figure S7. Example climb-out segment. (A) Climb-out emissions allocated at each 1 km segment and (B) Each 1 km segment is situated at height of its midpoint.

Table S6. 2016 population statistics (in millions of people) for the US by race-ethnicity at national scale and for urban and rural areas

	National	Urban areas only	% urban population of national total	Rural areas only	% rural population of national total
All race-ethnic groups	320.7	193.3	60%	127.5	40%
non-Hispanic White	196.4	100.3	51%	96.2	49%
White Hispanic	37.7	27.5	73%	10.2	27%
Black	40.9	30.3	74%	10.5	26%
Asian	17.0	14.4	85%	2.6	15%
Native American	2.6	1.0	39%	1.6	61%
Mixed/others	26.2	19.8	75%	6.4	25%
Hispanic	57.3	43.2	75%	14.1	25%

Data source: 2018 American Community Survey (ACS)

Table S7. Freight Analysis Framework Version 4 miles and calculated miles in this analysis using shortest route assumption

Mode	Billion ton-miles in 2017 from FAF v4 (T1)	Billion ton-miles using shortest distance assumption in this analysis (T2)	Ratio ($\frac{T1}{T2}$)	Ratio ($\frac{T1}{T2}$) statistics for all O-D pairs: median (range)
Truck	1,437.0	1,224.8	1.2	1.1 (0.5 – 6.0)
Rail	1,087.7	900.1	1.2	1.1 (0 – 7.1)
Barge	184.6	196.8	0.9	1.0 (0.04 – 55.4)
Air	2.23	2.24	0.99	1.0 (0 – 8.0)

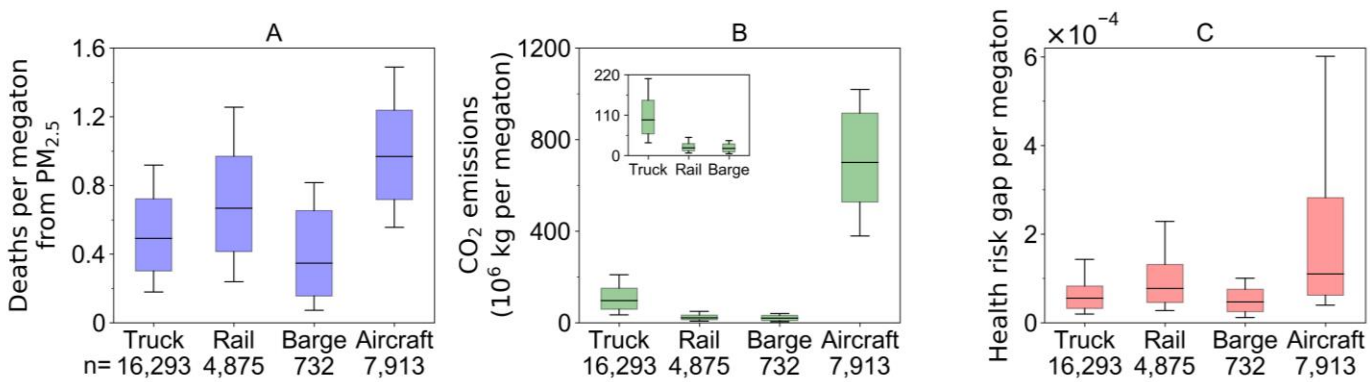

Figure S8. Boxplots showing distribution of metrics. Boxplot whiskers show 10th and 90th percentile. n represents no. of O-D pairs. (A) Deaths per megaton from each O-D pair by mode. (B) CO_2 emissions in kg per ton from each O-D pair by mode. (C) Health risk gap in deaths per 100,000 people per megaton from each O-D pair by mode.

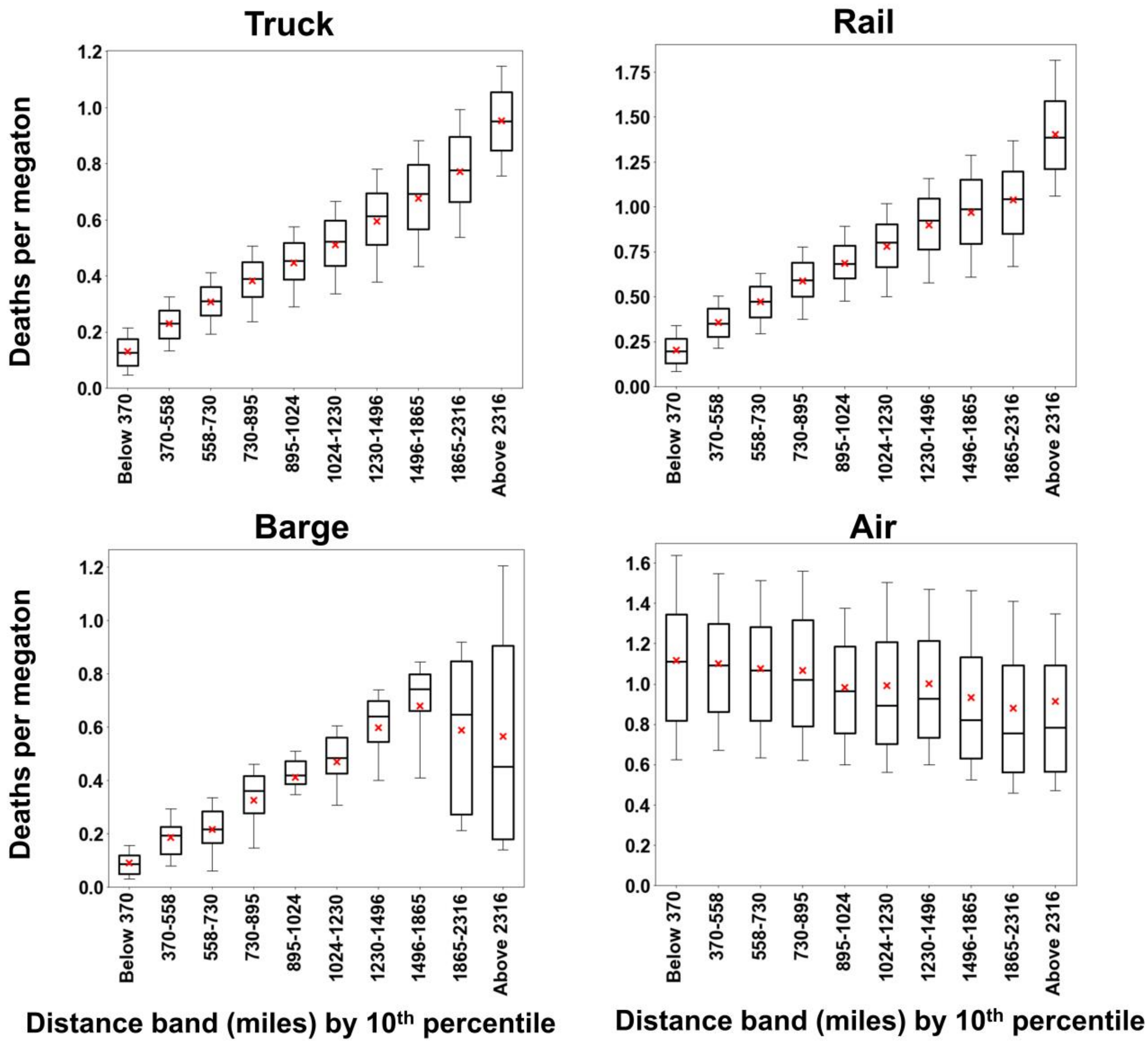

Figure S9. Boxplot showing distribution of deaths per megaton by O-D pair distance band for each mode. Each band represents 10th percentile of the O-D pair data. Boxplot whiskers show 10th and 90th percentile. Mean value is shown by red icon.

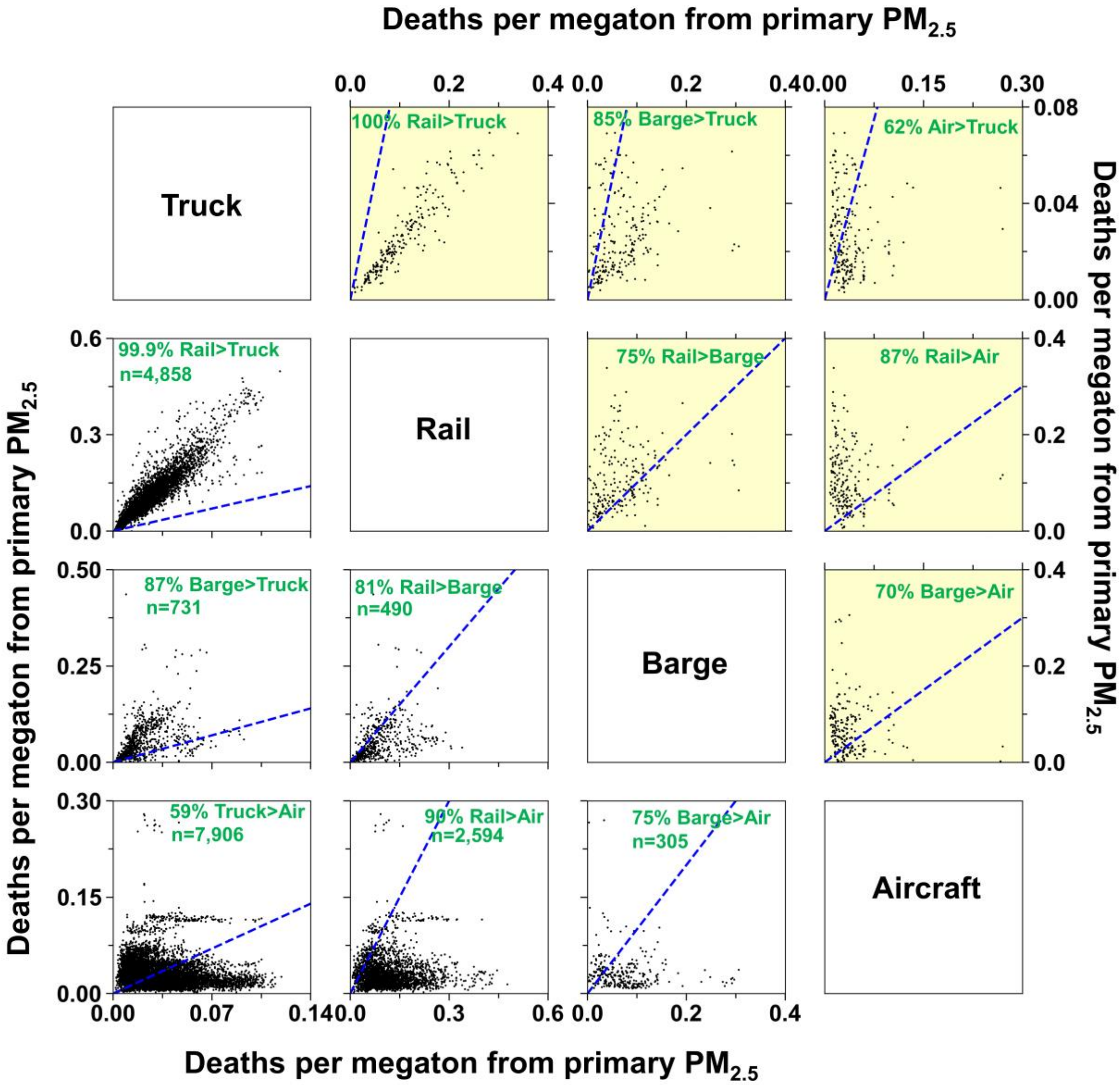

Figure S10. Pairwise comparison of deaths per megaton from primary $PM_{2.5}$ for each O-D pair.

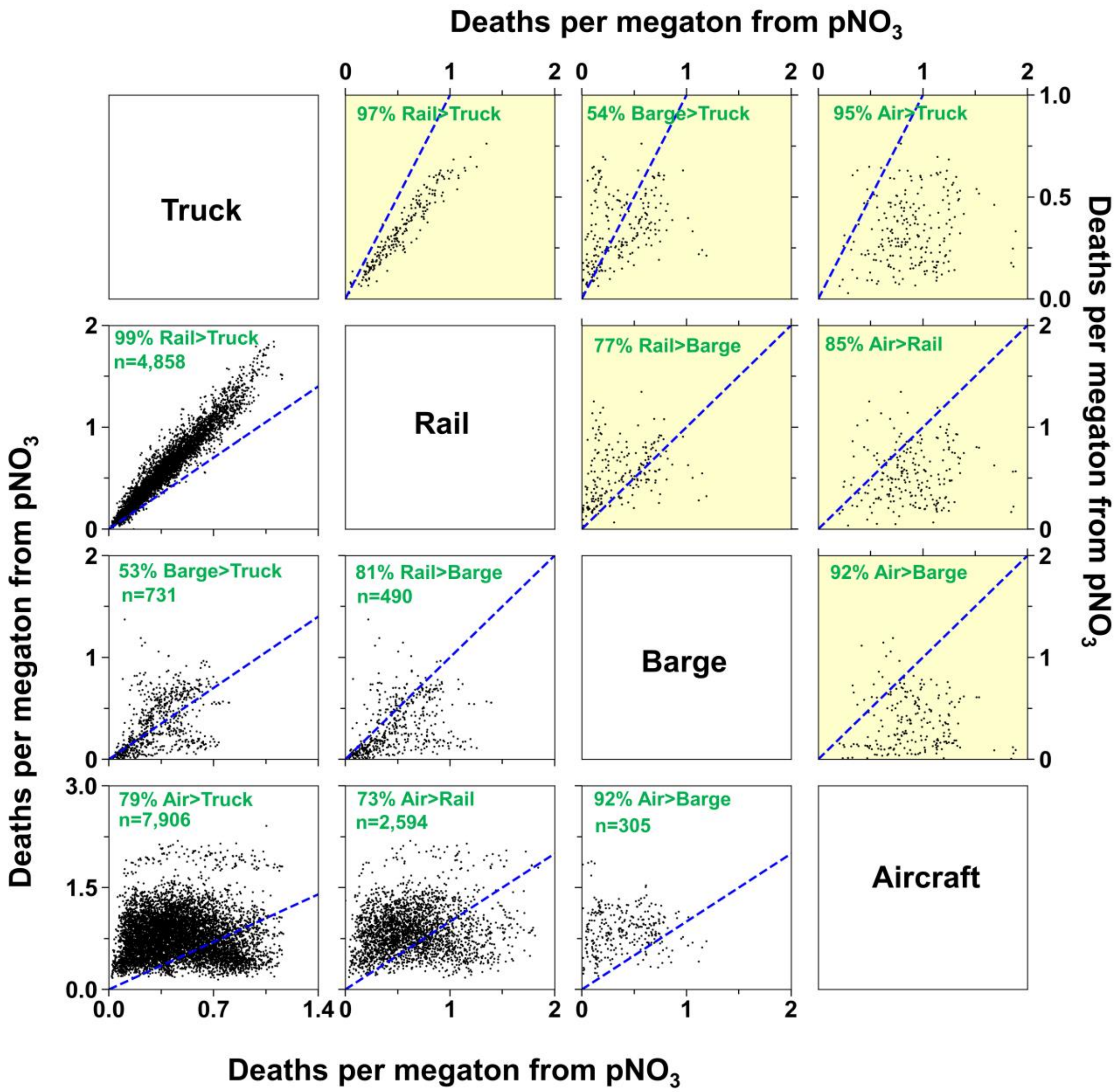

Figure S11. Pairwise comparison of deaths per megaton from pNO_3 for each O-D pair.

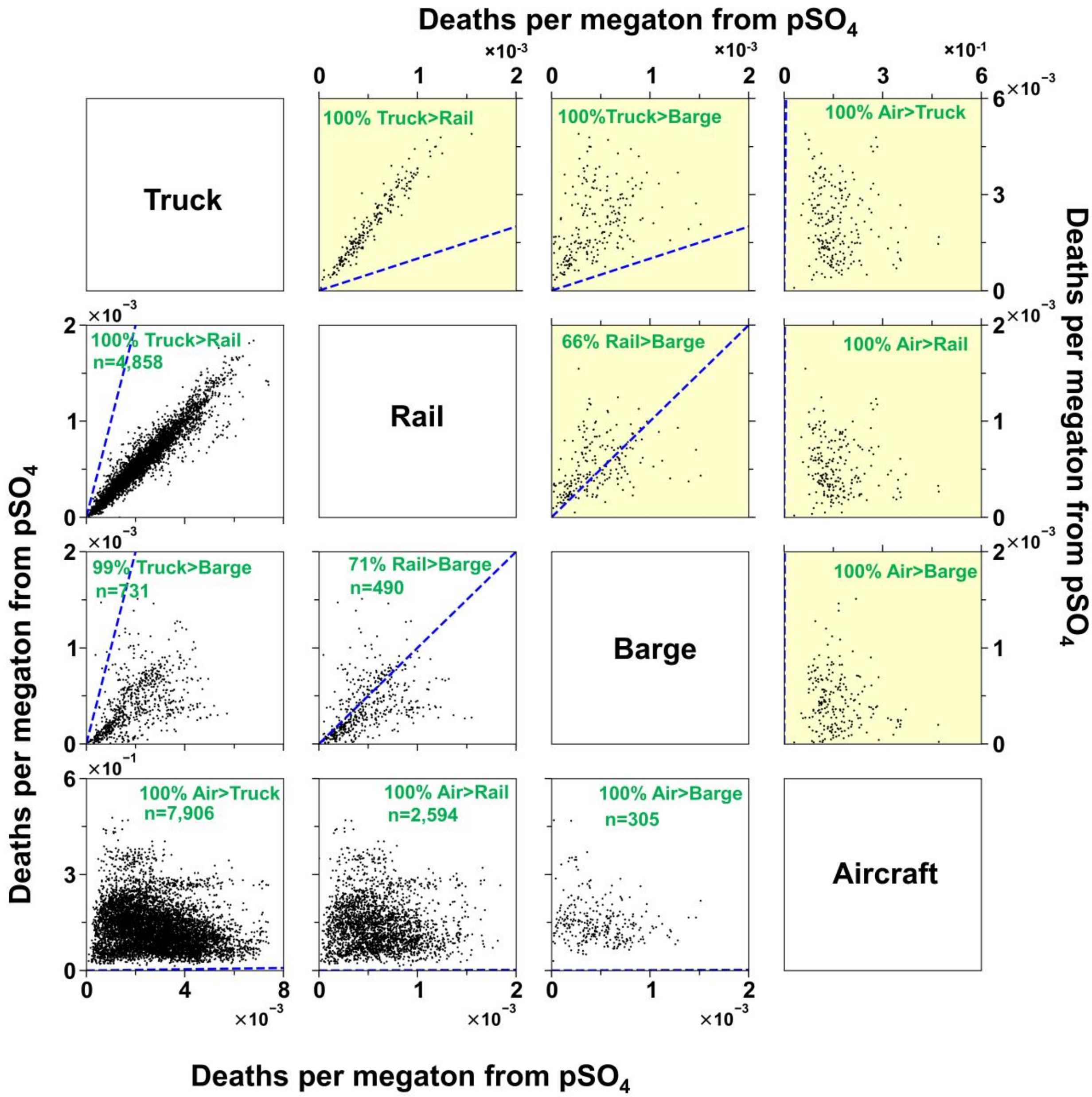

Figure S12. Pairwise comparison of deaths per megaton from pSO_4 for each O-D pair.

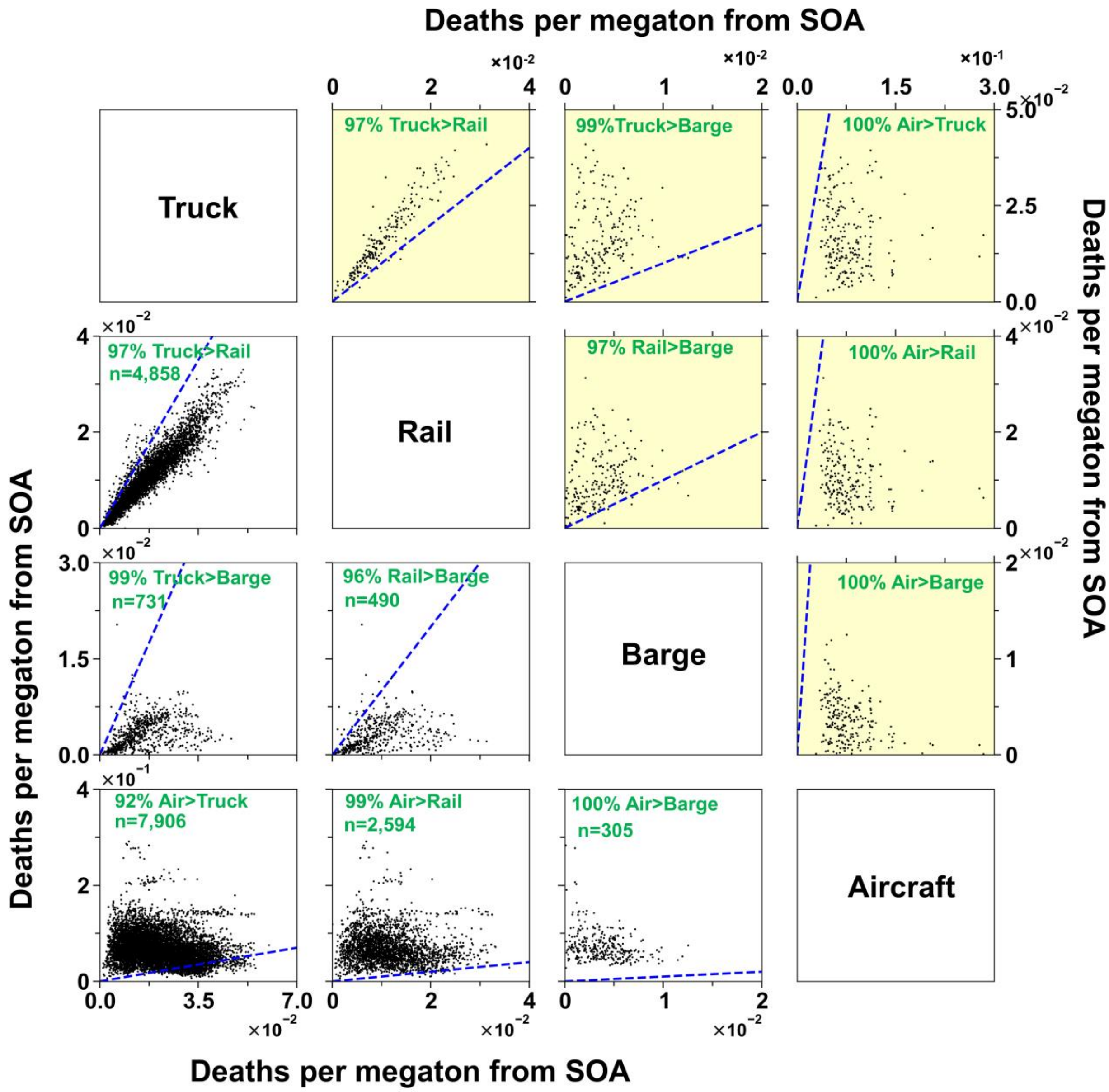

Figure S13. Pairwise comparison of deaths per megaton from SOA for each O-D pair.

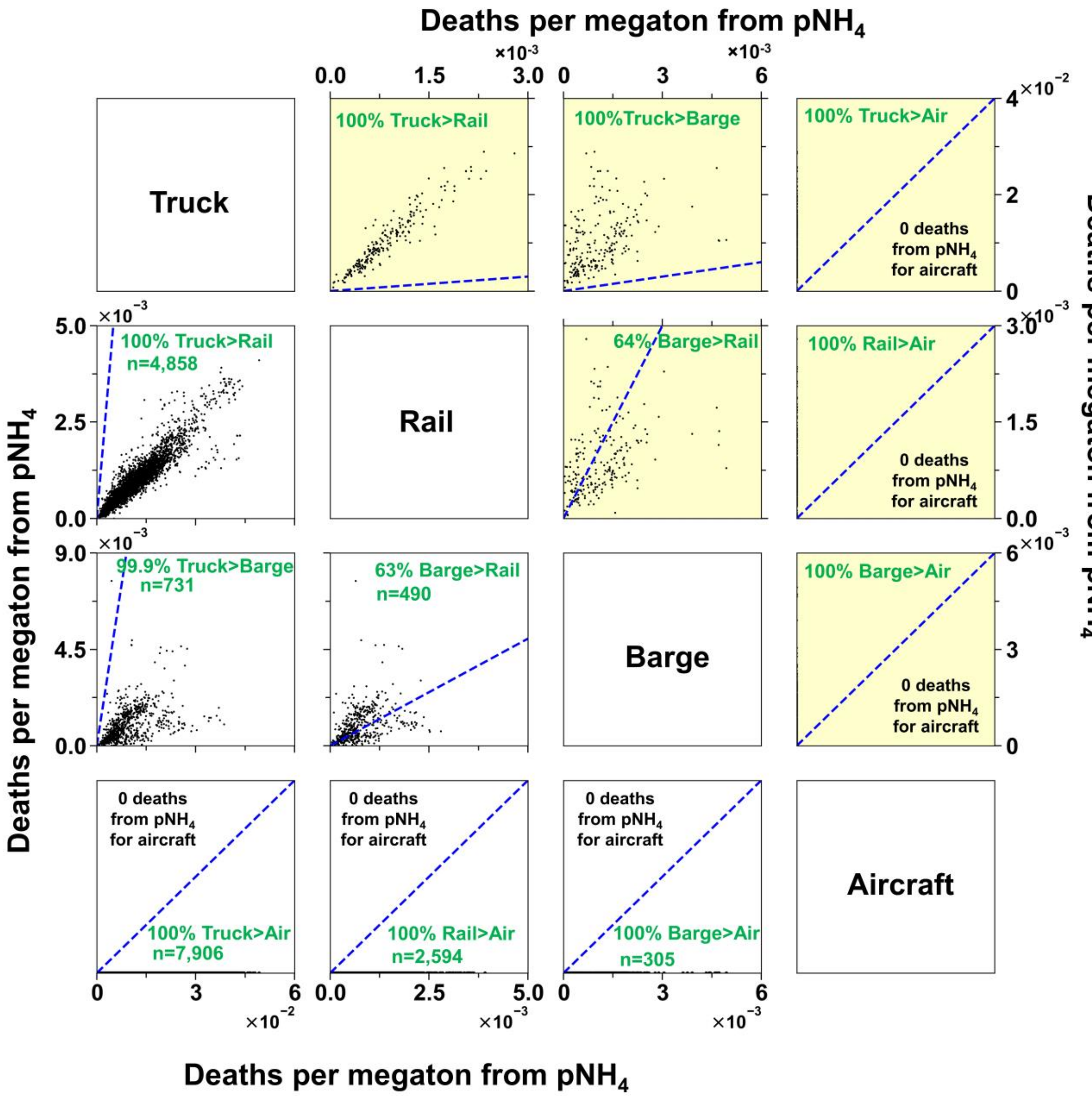

Figure S14. Pairwise comparison of deaths per megaton from pNH_4 for each O-D pair.

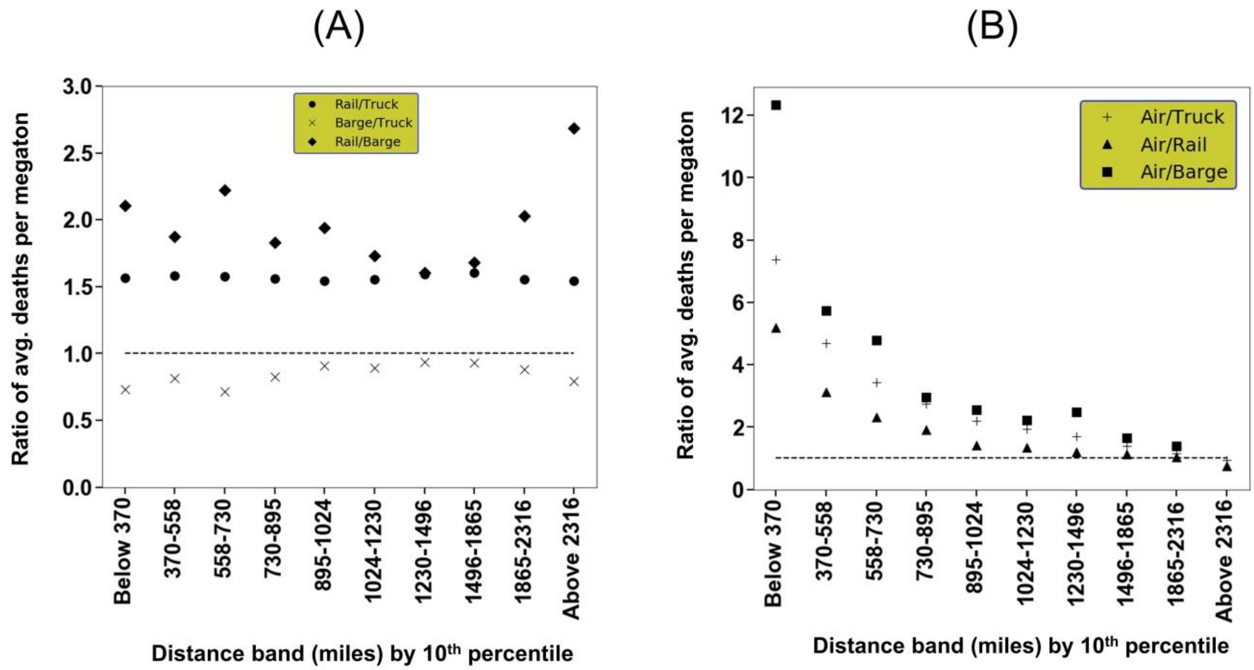

Figure S15. Pairwise modal comparison of average deaths per megaton by distance band. (A) comparison of non-aircraft modes and (B) comparison of aircraft with other modes. Each band represents 10th percentile of the O-D pair data. Ratio represents the ratio of average deaths per megaton of mode 1 to mode 2 as indicated. Dashed line represents y=1.

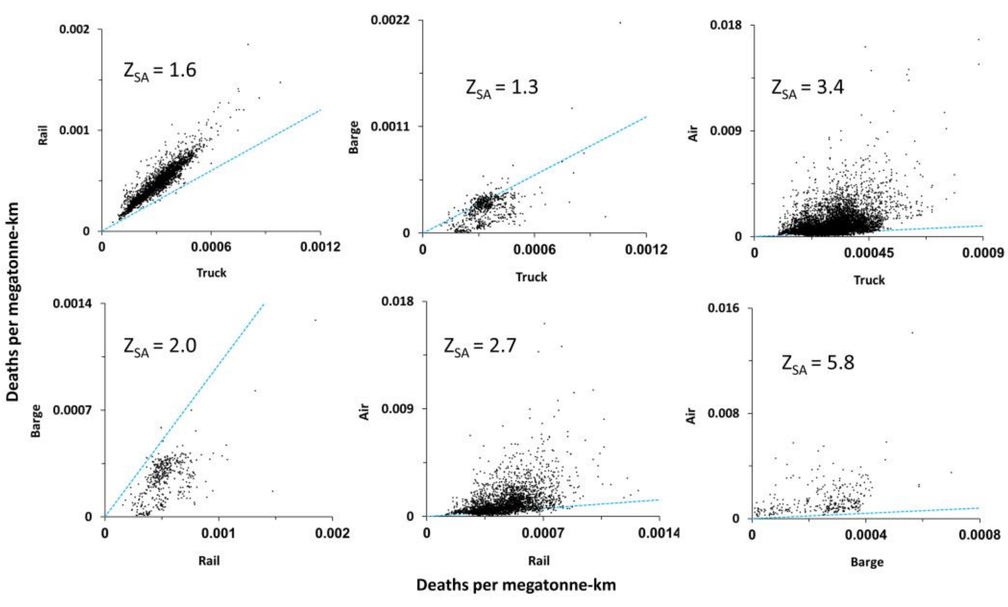

Figure S16. Pairwise health impacts from each origin-destination (O-D) pair by mode. Z_{SA} represents ratio of simple average of the mode with greater percentage to the mode with lower percentage.

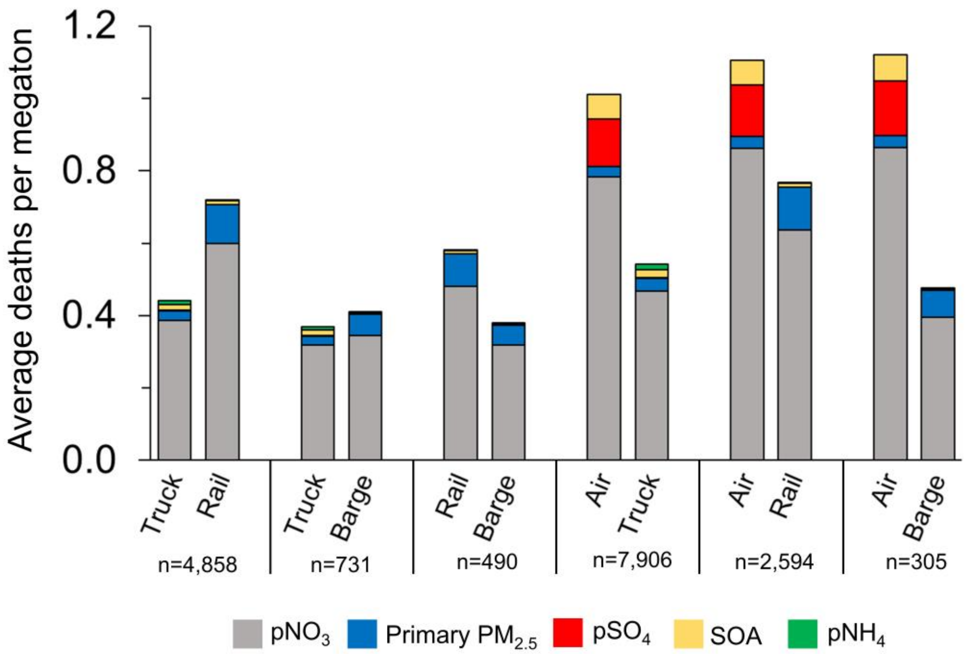

Figure S17. Pairwise modal comparison of average deaths per megaton by $PM_{2.5}$ precursor type.

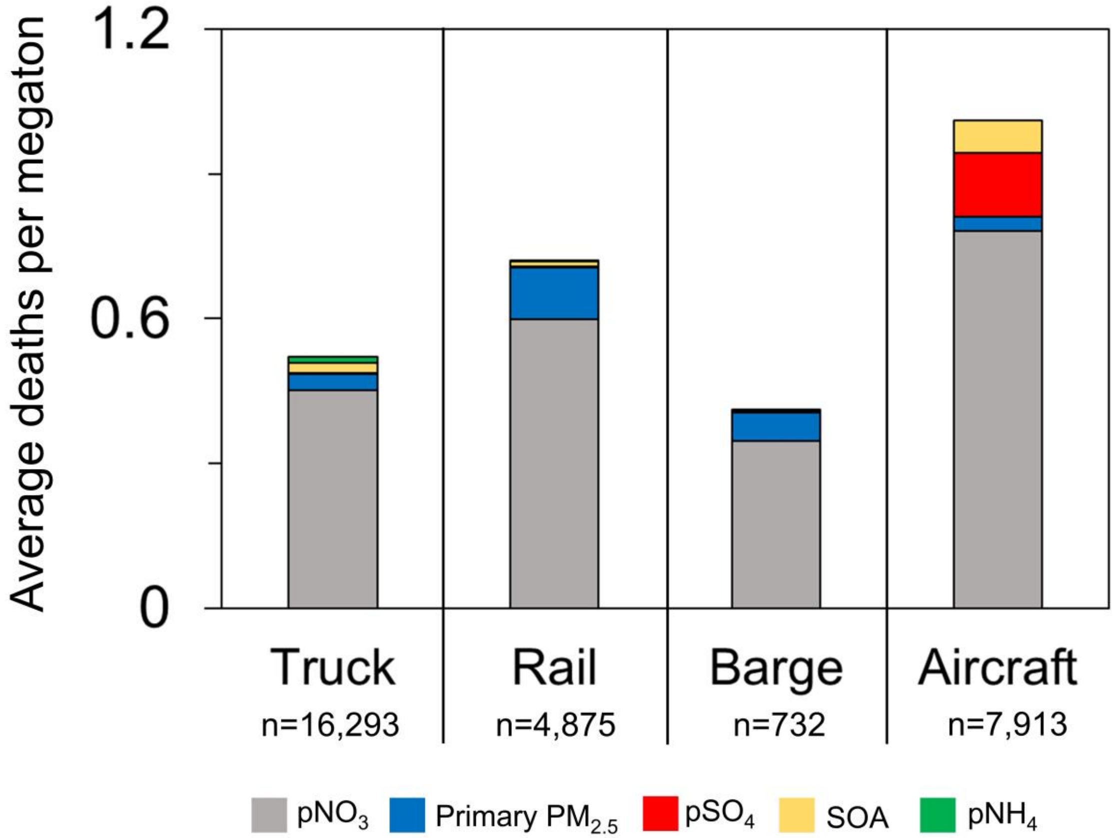

Figure S18. Average deaths per megaton by $PM_{2.5}$ precursor type for each mode for all O-D pairs.

Table S8. National scale total estimates of premature deaths, CO_2 emissions, and risk (deaths per 100,000 people) by mode

Mode	Billion Ton-Miles in 2017*	Mega tons in 2017*	Total deaths (all age groups)	Total deaths (age≥35 years)	Deaths (all ages) per billion ton-miles	Deaths (≥35 years) per billion ton-miles	Total CO_2 emissions (billion kg)	CO_2 emissions kg per ton-mile	Deaths per 100,000 people	Deaths per 100,000 people per billion ton-miles
Truck	1,437	3,378	660	611	0.46	0.43	124.00	0.086	0.206	1.43E-04
Rail	1,088	1,117	663	608	0.61	0.56	22.86	0.021	0.207	1.90E-04
Barge	185	291	65	61	0.35	0.33	3.20	0.017	0.020	1.09E-04
Air	2.23	1.73	1.82	1.67	0.81	0.75	1.31	0.588	0.00057	2.54E-04

*from US Department of Transportation's Freight Analysis Framework (FAF) data

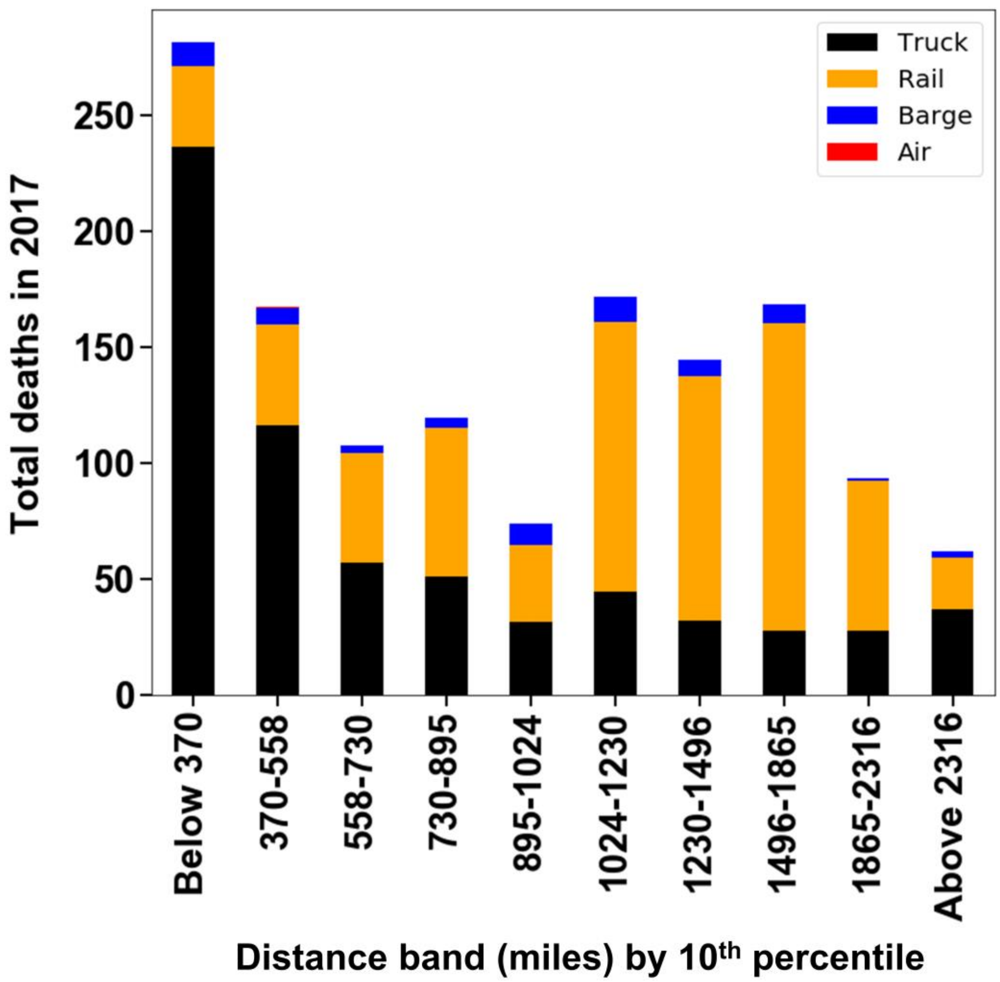

Figure S19. Total deaths in 2017 by distance band or each mode. Each band represents 10th percentile of the O-D pair data.

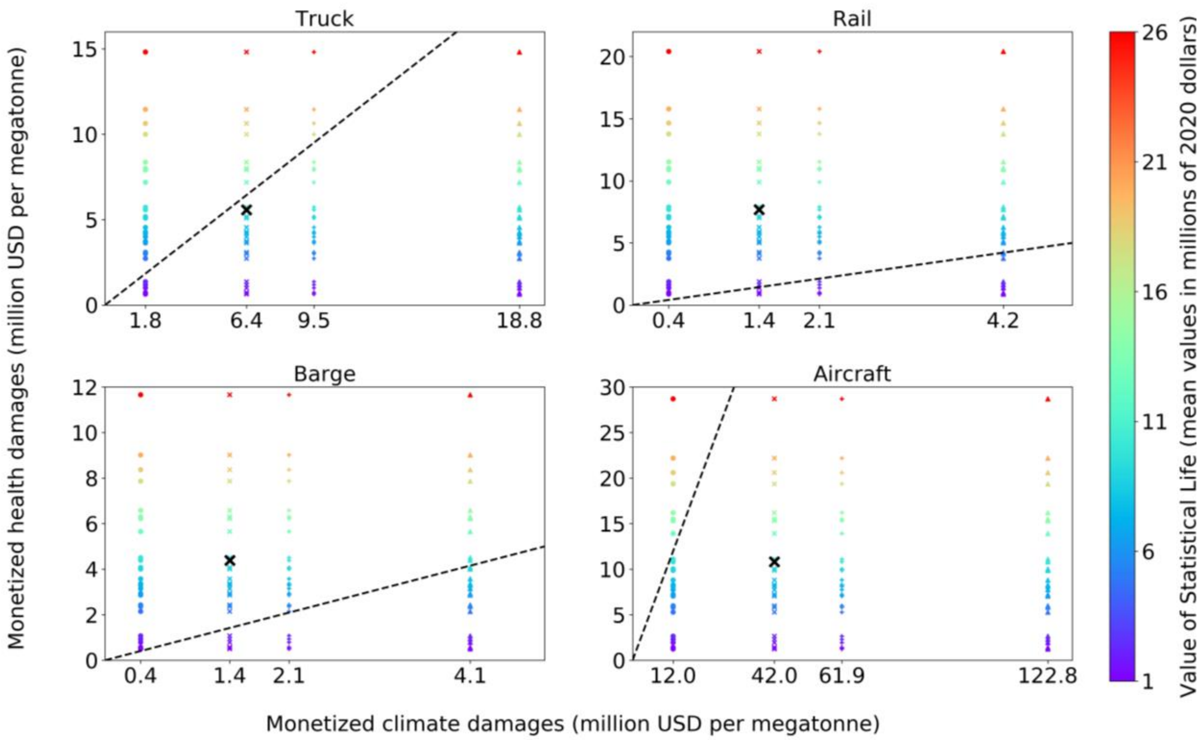

Figure S20. Sensitivity of monetized health and climate results to VSL (1.1 – 25.8 $million) and SCC (15, 54, 79, 157 $/tC), with 1:1 line (black-dashed) and base case values (black multiplication sign).

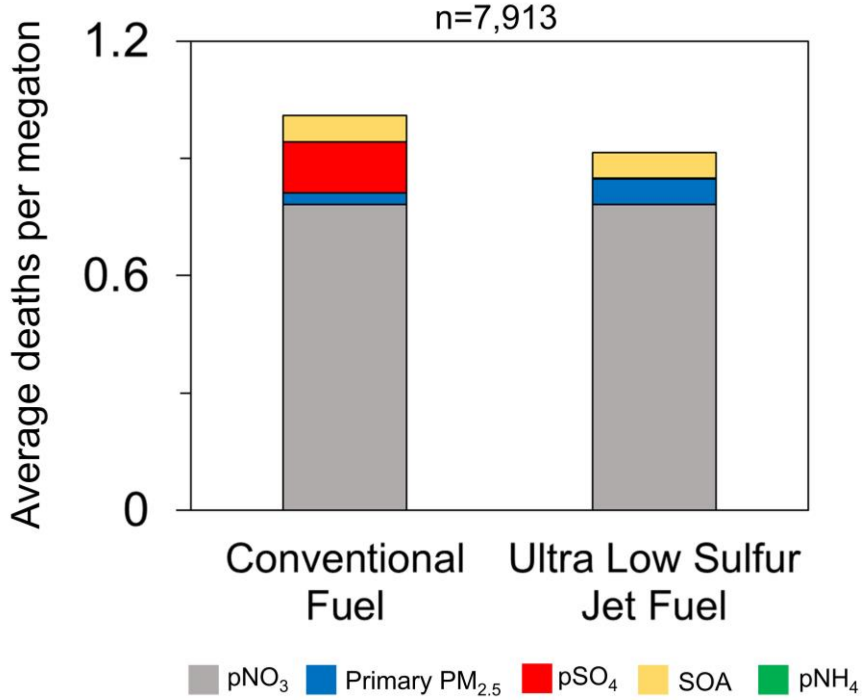

Figure S21. Aircraft average deaths per megaton by $PM_{2.5}$ precursor type using conventional fuel and Ultra Low Sulfur Petroleum Jet Fuel (ULSJ).

Table S9. Difference between health impacts from conventional jet fuel and ULSJ aircraft and truck, rail, and barge

Mode pair	Difference in deaths per megaton from *conventional jet fuel* aircraft and other mode	Difference in deaths per megaton from *ULSJ* aircraft and other mode
Air-Truck	0.47	0.37
Air-Rail	0.34	0.24
Air-Barge	0.65	0.53

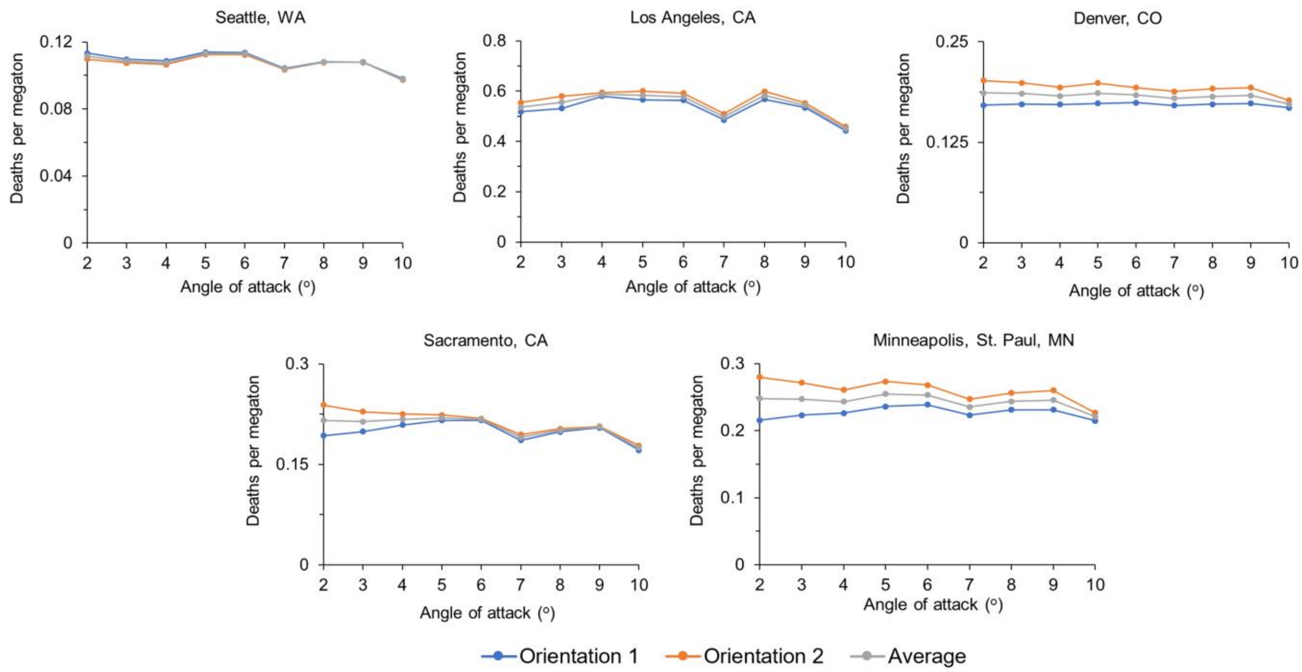

Figure S22. Average deaths per megaton from aircraft emissions as a function of Angle of Attack (climb-out angle) for selected airports. Orientation 1 is climb-out from one end of runway, Orientation 2 is climb-out from other end of runway, and average is arithmetic mean of Orientation 1 and Orientation 2.

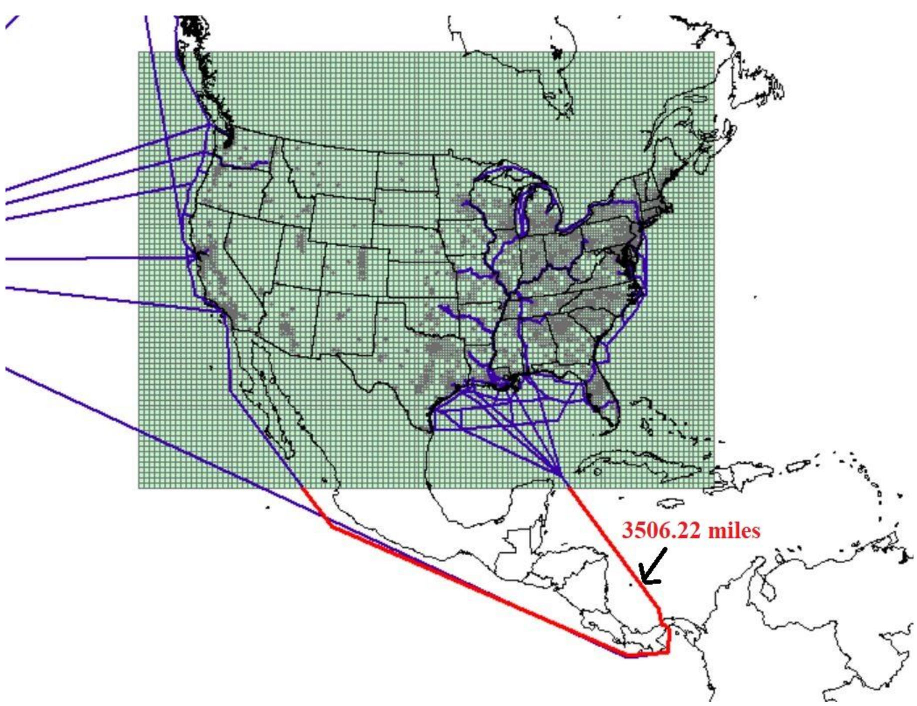

Figure S23. InMAP Source-Receptor Matrix (ISRM) grid, navigable waterway lines, and example of a barge route via Panama Canal. Length of red portion of waterway line is 3,506 miles. Waterways in the map are based on GIS files from the U.S. DOT's National Transportation Atlas Database (NTAD).

Table S10. Total deaths from barge for Panama bound journeys

O-D pairs via Panama Canal (between FAF regions)	Total deaths in US covered by InMAP grid	Total deaths from only Panama journey using average deaths per megatonne per mile from in-ocean journeys from other routes covered by InMAP grid	Percent total deaths from only Panama journey for each route
Arkansas to Los Angeles CA	1.9E-05	1.7E-05	47%
Arkansas to San Francisco CA	2.7E-05	1.9E-05	42%
Baton Rouge LA to Los Angeles CA	1.2E-05	3.1E-05	72%
Baton Rouge LA to San Francisco CA	2.3E-05	3.4E-05	60%
Corpus Christi TX to Los Angeles CA	1.7E-04	5.0E-04	75%
Corpus Christi TX to Rest of CA	2.0E-06	3.9E-06	66%
Corpus Christi TX to Rest of WA	1.3E-04	1.4E-04	53%
Corpus Christi TX to San Francisco CA	3.7E-02	5.9E-02	62%
Corpus Christi TX to Seattle WA	1.0E-04	1.4E-04	58%
Houston TX to Los Angeles CA	4.7E-03	9.4E-03	67%
Houston TX to Rest of CA	4.9E-05	7.6E-05	61%
Houston TX to Rest of WA	3.2E-03	3.0E-03	48%
Houston TX to San Francisco CA	7.9E-03	1.0E-02	56%
Houston TX to Seattle WA	2.5E-03	2.8E-03	53%
Lake Charles LA to Los Angeles CA	3.3E-05	1.0E-04	75%
Lake Charles LA to Rest of WA	2.8E-05	3.1E-05	53%
Lake Charles LA to San Francisco CA	6.7E-05	1.1E-04	62%
Mississippi to Los Angeles CA	8.8E-06	1.3E-05	60%
Mississippi to San Francisco CA	1.4E-05	1.5E-05	52%

New Orleans LA MS LA Part to Los Angeles CA	7.3E-05	2.4E-04	77%
New Orleans LA MS LA Part to Rest of WA	7.2E-05	8.3E-05	53%
New Orleans LA MS LA Part to San Francisco CA	1.6E-04	2.7E-04	63%
New Orleans LA MS LA Part to Seattle WA	5.5E-05	7.9E-05	59%
Rest of AL to Los Angeles CA	1.1E-05	9.9E-06	47%
Rest of LA to Los Angeles CA	3.2E-04	4.0E-04	56%
Rest of LA to Rest of CA	6.9E-07	7.3E-07	51%
Rest of LA to Rest of WA	1.8E-04	1.4E-04	43%
Rest of LA to San Francisco CA	4.8E-04	4.4E-04	48%
Rest of LA to Seattle WA	1.5E-04	1.3E-04	46%
Rest of TX to Los Angeles CA	2.3E-05	8.1E-05	78%
Rest of TX to Rest of WA	2.1E-05	2.4E-05	54%
Rest of TX to San Francisco CA	4.9E-05	8.5E-05	64%
Rest of TX to Seattle WA	1.5E-05	2.3E-05	60%

Total deaths for non-US portion (5,642 km not covered by InMAP grid, see Figure S23) is calculated using 4.6×10^{-5} average deaths per km per megatonne from other in-ocean journeys that are covered by InMAP grid. We find that part of other barge routes that are in the ocean or near the US coastline have average impacts of 4.6×10^{-5} deaths per megatonne per km (range: 2.1×10^{-5} – 11.9×10^{-5} deaths per megatonne per km among all those routes). Panama Canal-bound routes have a length of 5642 kms outside of the InMAP grid. This results in an average of 0.26 deaths per megatonne from in-ocean segment of barge route via Panama Canal

SI References

1. U.S. Department of Transportation, B.T.S. National Transportation Atlas Database. *Washington, D.C.* https://www.bts.gov/ntad (2021). Accessed September 2, 2020.

2. U.S. Department of Commerce, U.S. Census Bureau. TIGER/Line Shapefiles. *Washington, D.C.* https://www.census.gov/geographies/mapping-files/time-series/geo/tiger-line-file.2017.html (2020). Accessed September 2, 2020.

3. U.S. Department of Transportation, F. A. A. Aviation Environmental Design Tool (AEDT). *Washington, D.C.* https://aedt.faa.gov/ (2020). Accessed September 2, 2020.

4. Goodkind, A. L., Tessum, C. W., Coggins, J. S., Hill, J. D. & Marshall, J. D. Fine-Scale Damage Estimates of Particulate Matter Air Pollution Reveal Opportunities for Location-

Specific Mitigation of Emissions. *Proc. Natl. Acad. Sci. U. S. A.* **116**, 8775–8780 (2019).

5. U.S. Bureau of Labor Statistics. CPI Inflation Calculator. *Washington, D.C.* (2020). https://www.bls.gov/data/inflation_calculator.htm. Accessed February 2, 2022.

6. Turgut, E. T., Usanmaz, O., Cavcar, M., Dogeroglu, T. & Armutlu, K. Effects of Descent Flight-Path Angle on Fuel Consumption of Commercial Aircraft. *J. Aircr.* **56**, 313–323 (2019).

7. U.S. Department of Transportation, B. T. S. Freight Facts and Figures. *Washington, D.C.* https://www.bts.gov/product/freight-facts-and-figures (2019). Accessed September 2, 2020.

8. Amazon is changing its boxes. Here's why. *CNN Business.* https://www.cnn.com/2020/10/13/tech/amazon-box-ar-app/index.html (2020). Accessed February 2, 2022.