The Social Cost from Moving Crude Oil by Pipelines and Railroads: Evidence From the Bakken

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One sentence summary: In 2014 air pollution costs of moving crude oil were 6.7 times larger for rail than for pipelines and for both air pollution costs were 9x spill/accident costs.

Abstract: This paper provides new estimates of the air pollution and greenhouse gas costs from long distance transportation of domestically produced crude oil. While crude oil transportation has generated intense policy debate about rail and pipeline spills and accidents, an important externality – air pollution – has been largely overlooked. Using data for crude oil produced in North Dakota in 2014, this paper finds that the air pollution and greenhouse gas costs of transporting crude oil to coastal refineries were 15.7 cents per gallon and totaled more than $1.3 billion. These estimated environmental costs were 6.7 times larger for rail than for pipelines. For both rail and pipeline, air pollution costs of transporting crude were more than 9 times greater than estimates of the combined costs of spills and accidents.

Over the last decade, the transportation of domestically produced crude oil from oil fields to refineries has generated intense policy debate. While much of the debate has focused on a small number of high-profile rail and pipeline spills and accidents, another important dimension of crude oil transportation – air pollution – has been largely overlooked. Railroad locomotives burn diesel fuel, while crude oil pipelines use electricity to pump crude oil through the network. Much of this electricity is produced at power plants that burn fossil fuels. Both of these activities generate large quantities of pollutants, including nitrogen oxides (NO_x), sulfur dioxide (SO_2), fine particulate matter ($PM_{2.5}$), volatile organic compounds (VOCs), and carbon dioxide (CO_2).

This paper provides new estimates of the air pollution damages attributable to long distance transportation of domestically produced crude oil by rail and pipeline.[1] These air pollution estimates are compared to Pipeline and Hazardous Materials Safety Administration (PHMSA) estimates of spill and accident costs for rail and pipelines (*1*, *2*). We focus our analysis on North Dakota in 2014, because large volumes of domestically produced crude oil were transported from North Dakota by both rail and pipeline in 2014. To construct estimates of air pollution damage from transporting crude oil, this paper uses a novel combination of models and data sources. A key feature of our work is the detailed treatment of the location of emissions and subsequent exposure in the AP2 integrated assessment model. This feature is crucial because air pollution effects vary substantially by the location of emissions (*3*). For rail, we use shipment-level data from the Surface Transportation Board (STB) Confidential Waybill Sample. This nationally representative sample documents movements of crude oil by rail from county of origin to county of destination as well as any major junctions along the route. For pipelines, we use data on the quantity of oil flowing through each pipeline as well as the electricity consumed by pumping stations along each pipeline from Genscape, an oil industry data provider.

Empirical Method: To quantify the air pollution impact of trains, we combine per mile emissions factors with confidential quantity and route data to develop spatially disaggregated emissions estimates that are translated into monetized damage using the AP2 integrated assessment model.

In particular, we assume that each train has three locomotives and use EPA (*4*) projected locomotive emission rates for 2014. These emission rates for NO_x, SO_2,

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[1] Our estimates for air pollution exclude both the "first miles", which involve trucks or gathering pipelines, and the "last miles", if the oil is not delivered by pipeline or railroad directly to the refinery. 78 percent of domestically produced oil was delivered to refineries by either pipeline or railroad in 2014.

VOC, $PM_{2.5}$, and CO_2 are expressed in grams per gallon of diesel fuel consumed. We calculate the fuel consumed per mile for a train carrying crude oil as well as the return trip when the train is empty to calculate emissions per train per mile traveled. The Surface Transportation Board (STB) Confidential Waybill Sample provides us with the number of trains carrying crude oil and the number of tons moved by train along each possible rail route from North Dakota to final point of delivery in 2014. We construct the distance traveled by crude oil trains in each county for each possible route using GIS software. Specific routes were identified by combining information from the STB Confidential Waybill Sample with GIS maps of the North American railroad system developed by the Center for Transportation Analysis at the Oak Ridge National Laboratory. Finally, these data are combined to estimate, for every transited county, the total emissions and the emissions per million barrel-miles of each pollutant. (For a complete discussion of our empirical approach, see the supplementary materials.)

In accounting for pollution damage, a central issue in North Dakota is the extent to which trains carrying crude oil crowd out the rail transportation of other products. On one hand, railroads may operate with excess capacity and so one should count the full air pollution costs from additional rail traffic. Conversely, railroads may already operate at full capacity. In this case, additional rail traffic completely crowds out lower value products, and so has no net effect on air pollution from rail. Where does crude-by-rail from North Dakota fit on this continuum? North Dakota is heavily reliant on rail to move agricultural goods – 80 percent of grain was transported by rail in 2009 to 2012. If such shipments were crowded out, we would expect to see declines in agricultural shipments. We cannot present the total monthly number of carloads of agricultural products transported by rail from 2009-2014 due to data confidentiality considerations. Instead, Figure 1 plots the smoothed, monthly number of carloads after removing seasonal trends separately for three goods: oil, coal, and agricultural products. This figure demonstrates that, while the number of carloads of crude oil shipped by rail from North Dakota markedly increases over time, we do *not* see a corresponding decrease in the number of carloads of either coal or agricultural products shipped from North Dakota. Instead, the number of carloads of coal and agricultural products remains remarkably flat throughout our sample period. Based on this evidence, we assume in our analysis that railroads are operating with excess capacity.

To quantify the air pollution impact of pipelines, we use monthly pipeline-level crude oil flows and pumping station-level electricity consumption from Genscape. We employ the method developed by Graff-Zivin, Kotchen, Mansur (*6*) to link electricity demand shocks to changes in electricity generation at different power plants. These changes in electricity generation imply changes in the emissions of NO_x, SO_2, VOC, $PM_{2.5}$, and CO_2.

Our modeling does not capture train idling; rail congestion effects; first mile transportation by truck or gathering pipeline to railroads and long distance pipelines; and some last mile transportation from railroads and pipelines to refineries. As a result, we are likely estimating lower bounds of emissions.

We use the AP2 model to connect emissions from pipelines and trains to monetary damages (*3*, *7*). AP2 translates county-level emissions to county-level concentrations of air pollution in the counties affected by the pollution. The model calculates population exposure based on county-level population estimates provided by the U.S. Census. Exposures are translated into physical health effects using peer-reviewed, pollutant-specific concentration-response functions (*8*). Finally, AP2 monetizes health impacts utilizing the Value of a Statistical Life (VSL) approach for mortality risk used by the EPA (see supplemental materials). CO_2 emissions from power plants and locomotives are valued at the social cost of carbon estimated by the U.S. government (*9*).

As a point of comparison, PHMSA (*1*) present estimates of the social costs from accidents/spills stemming from rail transport of crude oil in their analysis of the regulatory impact of enhanced tank car standards and operational controls for high-hazard flammable trains. Translated into costs per barrel-mile using information on carloads, barrels per carload, and average distance, these estimates range from $214 at the low end to $381 per million-barrel miles using median values to $966 per million-barrel miles at the 95th percentile. There is a high level of uncertainty in these estimates because the probability of a very high cost event is difficult to determine.

Similarly, PHMSA's (*2*) preliminary regulatory impact analysis on pipeline safety contains estimates for 2004-2013 of the cost of spills and accidents for hazardous liquid pipelines. The estimates include fatalities, injuries, as well as property damage and are generally considered a lower bound on the true spill and accident costs from pipelines. We translate the PHMSA estimates into cost per million-barrel miles for crude oil; these costs range from $37-$95 per million-barrel miles with a central estimate of $62.

Results: We present our estimates of the air pollution and spill and accident costs for pipelines and rail in Table 1. Two things are worth noting. Air pollution damages for railroads are 6.7 times larger than the damages for pipelines. Also, the air pollution damages for both rail and pipeline are more than 9 times larger than their corresponding spill and accident costs.

Table 2 presents a more detailed pollutant-level comparison of the damages from crude oil transported by rail versus pipeline. It is important to emphasize that the air pollution damages from pipelines are due to emissions in counties with thermal power plants rather than counties with pipelines.

The left panel of Table 2 reports monetary air pollution costs, and the right panel reports emissions per million-barrel-miles. Rail emissions are higher for all pollutants except SO_2. The starkest difference between rail and pipeline is for NO_x. Emissions of NO_x are 30-times greater for rail than for pipelines, while monetary damages from these NO_x emissions are nearly 100-times larger for rail relative to pipelines. There are two reasons for this difference in NO_x emissions and damages. First, trains emit very high levels of NO_x per million barrel-miles. Second, each ton of pollutant emitted by trains is more harmful than the same ton of pollutant from pipelines because railroads run through cities. In contrast, pipelines use electricity; increased electricity generation may result in higher emissions from large thermal power plants typically located in rural areas. Thus, population exposures per ton of pollutant are vastly different for rail versus pipeline. This difference in exposure highlights that it is critical to model emissions and damages in a spatially resolved manner.

Table 3 presents air pollution damages for all trains carrying crude oil from North Dakota in 2014 – the vast majority of which was transported to refineries along the east, gulf and west coasts. Estimated pollution damages are $3,852 per million barrel-miles or 0.157 cents per gallon of crude oil transported. The costs are the highest for crude oil trains with destinations on the East Coast because these trains travel through more densely populated areas. However, most of the oil moving by pipeline is going to the Gulf Coast. Gulf Coast rail damages are $3,052 per million barrel-miles, which is lower than the sample average for rail but is much higher than the air pollution costs from pipelines of $569 per million barrel-miles.

The total estimated damages for oil shipped by rail from North Dakota in 2014 are greater than $1.3 billion. Our analysis suggests that about 90 deaths from air pollution exposure were attributable to shipments of crude by rail in 2014. Crude-by-rail also has additional environmental costs due to factors such as the damages from future climate change, increased rates of illness, reduced agricultural production, and accelerated depreciation of man-made materials (*10*).

This result is complementary to estimates of pollution damage attributable to the combustion of gasoline and diesel, which range from $0.23/gallon (*11*) to $0.52/gallon (*12*). Our findings suggest that the air pollution cost from *moving* a gallon of crude oil by rail were nearly equal to damages per gallon of gasoline or diesel *burned*. This result stems from the very high emission and fuel consumption rates for locomotives.

Discussion: Our analysis has two main findings. First, air pollution costs were 6.7 times larger for rail than for pipelines. We estimate that the damages for oil shipped by rail from North Dakota in 2014 were 15.7 cents per gallon, which resulted in overall environmental damages of $1.3 billion in 2014. Second, for both rail and pipelines the cost of air pollution was more than 9 times greater than the costs of spills and accidents. Moreover, while air pollution damages are purely social costs, spill and accident costs are at least partially borne by the companies responsible for these spills and accidents.

Although the transportation of crude oil by rail has fallen recently, crude-by-rail shipments are predicted to increase if oil prices remain above $50 per barrel. In addition, processed petroleum continues to be shipped in large quantities in 2015 and 2016. Our analysis is relevant for these other petroleum products and for rail traffic more broadly.

Companies make choices regarding how to transport crude oil based purely on their private costs. As such, public policy is necessary to present firms with the full cost, both private and social, of different transportation modes. While it is unclear if crude oil pipeline capacity investment is profitable at current oil prices, implementing a system of taxes that reflect external air pollution costs may help incentivize pipeline investment in the future. Though the proposed expansion of pipeline networks has generated a firestorm of public opposition, our findings may edify stakeholders in this debate by demonstrating that expanding crude oil pipeline capacity provides both private benefits to firms as well as air pollution benefits relative to transporting crude oil by rail.

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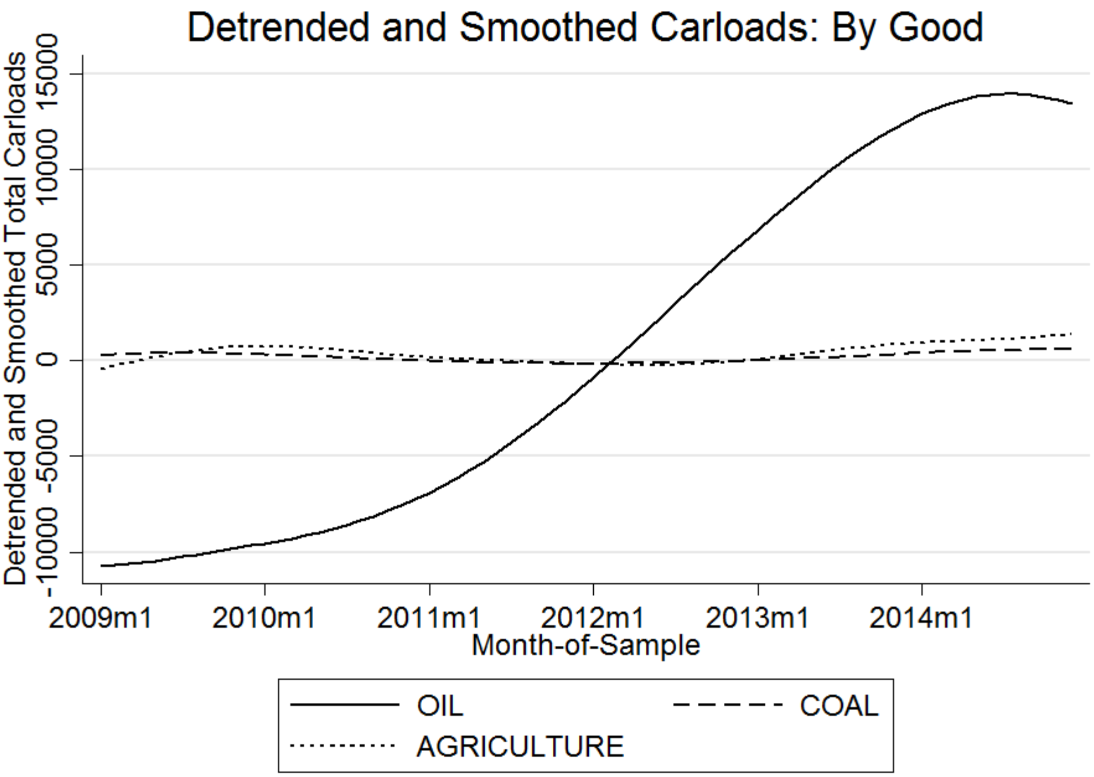
Figure 1: Monthly Rail Carloads by Commodity Group Originating in North Dakota



Notes: Based on STB Confidential Waybill Sample.

Table 1: Pipeline and Railroad Damages Per Million Barrel Miles

	Pipeline	Railroad
Air Pollution and Greenhouse Gas Damages[A]	\$569 (1,949)	\$3,852 (1,970)
Spill and Accident Damages[B]	\$62 (37 to 95)	\$381 (214 to 966)

A = Standard Deviations in parentheses
B = Spill and accident cost ranges in parentheses.

Table 2: Pipeline and Railroad Damages and Emissions by Pollutant

	Damage[A]		**Emissions**[B]	
Pollutant	**Pipeline**	**Railroad**	**Pipeline**	**Railroad**
NO_x	$28	$2,512	0.006	0.208
	(110)	(1,376)[C]	(0.021)	(0.108)
SO_2	$263	$189	0.009	0.005
	(844)	(118)	(0.032)	(0.003)
$PM_{2.5}$	$6	$295	0.001	0.006
	(8)	(208)	(0.003)	(0.003)
CO_2	$272	$686	5.672	15.732
	(997)	(371)	(20.79)	(8.177)
VOC	D	$118	D	0.009
		(76)		(0.005)

A = all values in $/million barrel-miles.
B = U.S. short tons/million barrel-miles.
C = Standard deviations in parenthesis.
D = not modeled.

Table 3: Air Pollution and Greenhouse Gas Damages from Crude-by-Rail: Averages over Routes from North Dakota

Destination	Costs per Gallon	Costs per Million Barrel-Miles	Barrels Shipped per Route	Distance Of Route (Miles)	Number of Routes
All Observed Waybills	$0.157 (0.097)[A]	$3,825 (1,970)	4,974,439 (5,366,218)	1,673 (388)	41 [B]
East Coast	$0.204 (0.044)	$4,416 (956)	5,451,223 (4,975,175)	1,939 (92)	13
Gulf Coast	$0.138 (0.027)	$3,052 (335)	6,276,440 (6,915,699)	1,899 (338)	8
West Coast	$0.090 (0.059)	$2,587 (1,593)	4,295,896 (5,113,411)	1,427 (346)	10

A = Standard Deviations in parentheses

B = The sum of the number of routes with destinations on the East Coast + Gulf Coast + West Coast does not equal 41 because some routes terminate in the Midwest and Ontario.

Appendix

1. Data

This section describes the sources of data for crude oil production and movement of crude oil to refineries by rail and pipeline.

Crude Oil Production and Movements

The Energy Information Administration (EIA) reports monthly crude oil production for each U.S. state. (*12*) EIA also reports PADD to PADD movements of crude oil by mode of transportation (*13, 14*).

Rail Routes to Refineries

Data on the location of rail networks used to transport crude oil across the United States are from the Center for Transportation Analysis (CTA) at Oak Ridge (*15*). Using GIS, we measured the distance in every county for every rail route carrying high volumes of crude oil from North Dakota. Because many lines run along county boundaries, a one-mile wide buffer along each line was computed, and the proportion of the buffer in each county was used to allocate rail miles to counties.

The analysis draws on confidential waybill data from 2009-2014 from the Surface Transportation Board (STB). These data are a stratified sample of all waybills; waybills corresponding to a higher number of carloads are sampled at a higher rate. The STB data include information on the class of goods being carried, origin county, destination county, major intermediate interchange points (such as Chicago, East St. Louis, and Detroit), rail carrier, tons shipped, and number of carloads. More detail on the STB's sampling procedure and the waybill sample is provided on the STB's website.

To generate GIS maps for each waybill, origin, termination, interchange and carrier information is combined with information taken from CTA's North America Rail Network Map. The CTA map identifies track ownership and class. For a given waybill, we use track ownership and class information to identify the most likely routes between nodes (origin/ destination/ interchange); assigning traffic to the highest class-of-track route owned by the waybill's carrier. In some cases, additional information was taken from state reports on the transit of crude by rail to verify our route identification. In cases where we could not uniquely identify the route taken by a train, traffic was split equally across potential routes.

Two other factors will affect emissions estimates: i) variation in speed over the course of a trip and ii) how longs train idle before, during, and after a trip. Variation in speed is important if locomotives move more slowly in urban areas, because air pollution costs per mile travelled are higher in areas with higher population densities. Speeds are often lower in urban areas due to speed limits and congestion. Emission factors are also higher while idling.

Industry reports indicate that trains spend considerable time idling in or near urban areas (*16, 17*). The Union Pacific website lists a number of reasons why locomotives spend time idling: "In a railroad operating environment, locomotive engines may be kept idling for several reasons: in a yard, they idle between work events; on the main line, they idle while meeting or passing other trains and to maintain air brake pressure; in cold temperatures, they idle to keep their cooling system from freezing." (*18*)

Chicago is particularly known for its congestion, slow speeds, and idling. For example, unit trains used to take 20 hours to travel 40 miles, but by 2014, that number had fallen to 14 hours (*19*). We have not been able to obtain additional data on variation in speed or on average time spent idling. Below, we present estimates of the per-hour air pollution costs of idling, demonstrating that idling at major junctions may have significant air pollution impacts.

Pipeline Routes to Refineries

We purchased data from Genscape, an industry intelligence provider, on monthly, crude oil flow for pipelines originating in the Bakken and monthly electricity consumption at selected pipeline pumping stations located between the Bakken and the Gulf Coast. In 2014, Genscape monitored 68 percent of the overall volume of crude oil transported from North Dakota. Genscape provided us with GIS information on pipelines as well as pumping stations. The analysis of pipelines is more complicated than rail because oil cannot be followed from origin to destination. In particular, the pipeline system is similar to the electricity grid; once oil enters, it is difficult to determine its precise path or final destination.

Constructing Figure 1 in the Main Text

Due to data confidentiality requirements, the STB does not allow us to display the total monthly number of carloads of different goods transported by rail from 2009-2014. To demonstrate that increased crude oil shipments from North Dakota are not crowding the rail shipment of other goods, we de-trend the monthly time series of carloads for each good, subtracting the total number of carloads for each good for each month-of-sample (ex: number of carloads of coal in Jan. 2012) by the month-of-year average number of carloads (ex: number of carloads of coal in the month of January averaged over the years 2009-2014). Figure 1 in the main text plots the monthly de-trended number of carloads separately for three goods: oil, coal, and agricultural products; these monthly time series are smoothed using the LOWESS method to further ensure data confidentiality.

2. Methodology

This section describes how air pollution costs are computed. To estimate costs, the AP2 integrated assessment model requires information on the quantity and the location of pollutants emitted. Using this information, the AP2 generates damage estimates for ground level (locomotive) and point source (power plant) emissions by location of discharge. (*20*) and (*21*) provide evidence that the AP2 model accurately predicts monitor-level outcomes. Specifically, see Figure A2 in the supplemental materials for (*20*) and the discussion on pages 2 and 3 of the appendix of (*21*).

Rail Emissions

To determine the quantity of locomotive pollutants, we adopt an approach similar to the one used in a recent Environmental Impact Statement (EIS) conducted for the Keystone XL pipeline (*22*). Based on analysis done by the United States Department of State, Appendix Y of (*23*), our analysis assumes there are three locomotives per train. Discussions with industry railroad consultants suggest that this is typical. The EPA projected locomotive emission rates for 2014 (*24*) are nearly identical to the rates used in the Keystone XL documentation on rail (*23*). These emission rates for NO_x, SO_2, VOC, $PM_{2.5}$, and CO_2 are expressed in grams per gallon of diesel fuel consumed. To operationalize these emission rates, it is necessary to estimate fuel consumption.

We distinguish between outbound (loaded) trains and empty trains returning to North Dakota. Since trains carrying the weight of crude oil work harder, they consume more fuel and therefore emit more pollution per mile traveled. For outbound trains, we assume that 480 tons of cargo (crude) is transported one mile for each gallon of diesel fuel (*23, 25*). Ton-miles per gallon are converted to grams per mile based on the following calculation. First, each gallon of Bakken crude weighs 6.79 pounds (*23*). Each barrel contains 42 gallons. We assume a typical train carries 75,000 barrels. This agrees closely with Genscape's estimate of 74,880 barrels for trains loading in North Dakota. The Keystone XL documentation on rail (*23*) assumes 67,600 barrels per train. If 67,600 rather than 75,000 barrels per train is the correct number, our numbers would be biased down. Thus, emissions of pollutant (p) per train (t), expressed in grams per mile is given by $E_{p,t}$:

$$E_{p,t} = 3\left(\frac{locomotives}{train}\right) \times 6.79\left(\frac{lbs.}{gal.}\right) \times 42\left(\frac{gal.}{bbl.}\right) \times (7.5\times10^{4})\left(\frac{bbl.}{train}\right) \times \left(480\,\frac{ton-miles.}{gal}\right)^{-1} \times \left((2\times10^{3})\,\frac{lbs.}{ton}\right)^{-1} \times E_p\left(\frac{grams}{gal.}\right)$$

Returning trains move 0.14 miles per gallon of diesel consumed (*23*). Thus, converting emission rates in grams/gallon to grams per mile is straightforward for empty trains.

However, basing fuel consumption on average ton-miles per gallon does not capture the fact that trains are more likely to idle or move at slower speeds in major urban areas. For example, unit trains take 14 hours to travel through Chicago (*19*). Our default approach does not reflect stoppages at junctions.

Thus, we estimate emissions while trains are sitting at junctions along the rail routes as a sensitivity analysis. The STB data note major train junctions; the three major junction locations are: Chicago, East St. Louis, and Detroit. The STB also reports time in hours that trains spent switching and in rail yards as well as total fuel consumption while switching. Combining fuel consumption with the gram per gallon emissions data yields estimates of emissions per hour spent in rail yards. Since data on time spent at junctions are not available, we estimate emissions per train-hour spent idling. Averaging across all routes that pass through one of the above junctions, we estimate social costs of $0.05 per barrel per hour spent idling. Idling in Chicago and East St. Louis, Illinois produces damages of $0.06 and $0.03 per barrel-hour, respectively. In Detroit, damages per barrel-hour are roughly $0.04 per barrel-hour. Table A.1 also indicates that the largest shares of damages from idling come from NO_x and $PM_{2.5}$ emissions.

Table A.1. Estimated Air Pollution and Greenhouse Gas Damages from Idling Trains.

Junction Site	**All Pollutants**	**NO_x**	**SO_2**	**VOC**	**$PM_{2.5}$**	**CO_2**
Chicago, IL	0.055[1]	0.039	0.002	0.003	0.009	0.003
East St. Louis, IL	0.027	0.021	0.001	0.001	0.002	0.003
Detroit, MI	0.035	0.023	0.001	0.002	0.005	0.003
Average	0.048	0.034	0.001	0.002	0.007	0.003

1 = All values in table A.1 are expressed in terms of $ per gallon per hour spent idling.

Pipeline Emissions

We also calculate the emissions from the electricity consumed by the pumping stations that pump crude oil through pipelines. The Genscape data includes monthly, station-level electricity consumption and pipeline-level crude oil flows. We employ the method developed by Graff-Zivin, Kotchen, and Mansur *(5)* to link power demand shocks to electricity generation and emission responses. In this method, an electricity demand shock in a given North American Electric Reliability Corporation (NERC) region yields electricity generation responses at many different power plants; each power plant has a distinct emission rate for each of many different pollutants (in tons per MWh). The adapted methodology of Graff-Zivin, Kotchen, Mansur *(5), which was* subsequently used in (*26*), is used herein. This method employs power plant emissions data from 2010-2012 to estimate emissions rates for each pollutant in each NERC region; this will likely overstate 2014 emissions due to decreases in the percentage of U.S. electricity generation from coal-fired sources. Note that United States Department of State Keystone XL analysis (*3*) only considers power plant emissions of CO_2. Analysis of emissions of criteria pollutants from power plants was not required for the purposes of the National Environmental Policy Review. Emissions of pollutant (p) from pumping station (s), are given by:

$$E_{p,s} = e_s \times \sum_{m=1}^{P} I_m \, f_{p,m}$$

where e_s is the annual electricity consumed by pumping station s (in MWh). I_m is an indicator function denoting whether power plant (m) responds to electricity demanded at pumping station s. This indicator function varies by the plant location and by the NERC region location of each pumping station. Finally, $f_{p,m}$ denotes plant (*m's*) emissions rate for pollutant *p*; this pollutant-specific emissions rate varies at the NERC region level.

Not all pumping stations in the database are monitored for electricity consumption. We use the electricity demand and oil flows reported for the monitored stations to estimate power consumption and crude flows for unmonitored stations on the same pipeline. For example, if the average daily electricity consumption of four monitored stations on the same pipeline is X megawatt hours, then we assign X megawatt hours to all unmonitored stations on the same pipeline.

Methodology for Calculating Damages

We next turn to the estimation of the social cost of these emissions estimates for trains and pipelines. This social cost calculation is based on the AP2 integrated assessment model (*6*). To value emissions from pipelines and locomotives, we employ marginal damage estimates (in dollars/U.S. short ton) by county and by power plant. The marginal damages are calculated based on emissions, population, and vital statistics from 2011; 2011 is the most recent year for which there are comprehensive emission inventories in the United States (*21*). The algorithm used to calculate marginal damages begins by calculating the total damage associated with baseline emissions from all sources in 2011 (*27, 3*). Then, one ton of one pollutant is added to one source. The model re-computes concentrations, exposures, physical effects, and damages with this additional ton of the pollutant. Since nothing else changes from the baseline scenario except the additional ton added to baseline emissions at the specified source, the difference between the two model runs is the marginal damage (in \$/ton). The model repeats this algorithm over $PM_{2.5}$, SO_2, NO_x, and VOCs from roughly 10,000 ground level and point sources in the U.S.

The empirical estimation of marginal damages requires several steps. The AP2 model connects emissions to concentrations of air pollution and population exposure. Population exposure relies on U.S. Census county-level population estimates. Population exposures are then translated into physical health effects using peer-reviewed concentration-response function. The most important (in terms of the share of damage) functional relationship is the one between exposure to $PM_{2.5}$ and adult mortality rates. The current paper uses Krewski et al., (7), which is employed by the USEPA in its regulatory impact analyses for air pollution (*28, 29*).

To monetize mortality risk, AP2 uses the Value of a Statistical Life (VSL) approach. The AP2 uses the USEPA's VSL of roughly \$10 million (2014 USD), which is standard in both the academic literature and in policy analyses (*29*). This \$10 million number is based on the average of roughly 30 revealed and stated preference studies that each estimated a value of statistical life. Importantly, this VSL is applied uniformly across all exposed populations. Finally, CO_2 emissions from power plants and locomotives are valued at about \$40/ton, which is the social cost of carbon estimated by the U.S. government (*8*).

Importantly, the \$/ton damage of pollutant (p) released from location (c) is a spatial sum of impacts over multiple counties (r) that receive pollution from a given source. Note that $D^{b}_{r,p,t}$ reflects the damage in county (r) from pollutant (p) at time (t) with reported emissions, while $D^{+1}_{r,p,t}$ is the damage when an additional ton of (p) is added to reported baseline emissions.

$$MD_{p,c,t} = \sum_{r=1}^{R} \left(D^{+1}_{r,p,t} - D^{b}_{r,p,t} \right)$$

Thus, if a locomotive emits a mixture of VOC, SO_2, $PM_{2.5}$, and NO_x in a particular county along a rail route, AP2 tabulates damages from those emissions that manifest in potentially many counties as emissions disperse into nearby counties. Similarly, if a power plant responds to power demand at a pumping station, the damage attributed to emissions from that facility reflect the dispersion characteristics associated with its smokestack and local weather conditions. As shown in the equation below, AP2 is used to calculate the product of emissions and marginal damage by pollutant (p) and location (c). Emissions differ by transportation mode (m). Total damage ($D_{i,m}$) produced by a transportation mode (m) along a route (i) – either a pipeline or a rail route - is the sum of the product of emissions and marginal damages across pollutants (p) and counties or power plants from which pollution is released (c).

$$D_{i,m} = \sum_{c=1}^{C} \sum_{p=1}^{5} \left(MD_{p,c} \times E_{p,c,m} \right)$$

Damage from accidents and spills

PHMSA conducted a regulatory impact analysis (RIA) on Enhanced Tank Car Standards and Operational Controls for High-Hazard Flammable Trains (*1*). The analysis developed estimates of the cost of spills and accidents per carload of either crude oil or ethanol, which include property damage, cleanup costs, injury costs and mortality costs. This RIA presents a range of social costs that can be translated into barrel miles using information on carloads, barrels per carload, and average distance.[1] These estimates range from $214 at the low end to $381 per million-barrel miles using median values to $966 per million-barrel miles at the 95th percentile. The range is large because the probability of a very high cost event is difficult to determine.

PHMSA's (2015) preliminary regulatory impact analysis (RIA) on pipeline safety contains estimates for 2004-2013 of the cost of spills and accidents for hazardous liquid pipelines, separately for high consequence areas (HCA) and non-high consequence areas (non-HCA). "HL [hazardous liquids] pipelines carry crude oil, refined petroleum products, volatile liquids (such as propane, butane, and ethylene), carbon dioxide, and anhydrous ammonia." (*2*, p. 15) For hazardous liquids, high consequence areas (HCAs) "include populated areas, drinking water sources, and unusually sensitive ecological areas." (*2*, p. 1) Forty-three percent of pipeline miles are in HCA. The annual accident costs per pipeline mile are $919 for non-HCA and $2,392 for HCA. The estimates include fatalities, injuries, and property damage and are generally considered lower bound estimates: "there are important social costs completely missing from the estimates and some costs that are likely underestimates of the true social costs." (*2*, p. 19) Though these numbers are not calculated separately by product type, we can translate the PHMSA estimates into cost per barrel mile for crude oil. It is worth noting that in Appendix A, which lists preventable incidents that occurred during 2010-2014, 12 of the 20 highest cost incidents involved crude oil. In 2013, there were 151,423 miles of crude oil gathering, trunk, and product trunk pipelines (30). These pipelines account for a large fraction of the 191,478 miles of hazardous liquids pipeline used in (*2*). Computing the weighted average cost for the HCA and non-HCA pipelines yields a social cost per pipeline mile of $1,552. In 2013, there were 25 million barrel-miles of crude oil and petroleum products moved per mile of pipeline. Thus, the cost of spills and accidents per million-barrel miles of crude oil and petroleum products is $62. If all of the crude oil and petroleum products were moved in non-HCAs at a spill and accident cost of $919 per mile, this would result in a lower bound estimate of $37 per million-barrel miles. If all of the crude oil and petroleum products were moved in HCAs at a cost of $2,392 per mile, our upper bound cost estimate would be $95

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[1] PHMSA (1) Table EB14, p. 111. Carloads (1,119,000) are from p. 82, barrels per carload are assumed to be 750, and distance (1000 miles) is from p. 200. The costs are not reported separately for crude oil and ethanol, but the average cost per gallon for ethanol and crude oil used in the estimates ($200) is only slightly less than the estimate for crude oil spills, ($211). As a result, our estimates are biased down slightly.

per million-barrel miles. We utilize these cost estimates in order to compare our estimated pollution damages to the risks from spills and accidents.