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ABSTRACT

This paper constructs new estimates of the air pollution and greenhouse gas costs from long-distance movement of petroleum products by rail and pipelines. While crude oil transportation has generated intense policy debate about rail and pipeline spills and accidents, important externalities – air pollution and greenhouse gas costs – have been largely overlooked. Using data for crude oil transported out of North Dakota in 2014, this paper finds that air pollution and greenhouse gas costs are nearly twice as large for rail as for pipelines. Moreover, our estimates of air pollution and greenhouse gas costs are much larger than estimates of spill and accidents costs. In particular, they are more than twice as big for rail and more than eight times as big for pipelines. Our findings indicate that the policy debate surrounding crude oil transportation has put too much relative weight on accidents and spills, while overlooking a far more serious source of external cost: air pollution and greenhouse gas emissions.

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1. Introduction

This paper constructs new estimates of the air pollution, greenhouse gas, and spill and accident costs associated with the long-distance movement of petroleum products by rail and pipelines. Movements of petroleum products, particularly crude oil, have received enormous media attention. Almost all of the attention has focused on spill and accident costs despite the fact that air pollution and greenhouse gas costs are also likely to be significant.

Pollution emissions for pipelines and rail differ from one another in three important ways. First, while emissions from trains occur along the transportation route, emissions from pipelines manifest at the power plants that generate the electricity consumed by pumping stations. The distance between these power plants and the associated pumping stations can be quite large. Second, ground-level emissions, such as those from locomotives, tend to be more harmful than the same level of emissions released from tall smokestacks at power stations (Muller and Mendelsohn, 2009). Third, the existing railroad infrastructure moves goods through population centers. In contrast, power plants are typically located in less densely-populated areas. This difference matters for pollution exposure, because the emissions from trains moving through cities are likely to contact many more people than those emitted at power plants.

To construct our estimates, we use data on locomotive diesel consumption, pipeline pumping station electricity consumption, locomotive and power plant emission factors, and the AP2 integrated assessment model, which maps county level emissions to costs for counties affected by the emissions. Estimates are constructed for movements of crude oil from North Dakota in 2014, a year in which roughly half of the crude oil was shipped to refineries by rail and half was shipped by pipelines. Locomotive diesel consumption is estimated based on movements of crude oil from the Surface Transportation Confidential Waybill Sample and industry data on average ton-miles per gallon. Our approach to estimating diesel consumption is similar to that taken by U.S. Department of State (2014). Pipeline pumping station electricity data is from Genscape (2014). The AP2 integrated assessment model estimates changes in county-level air pollution based on changes in emissions and an air transport model. The AP2 model then uses census data on population and other county characteristics together with peer reviewed concentration-response functions and valuations of outcomes used by the EPA in order to construct estimates of county-level damages. We construct estimates of spill and accident costs from Pipeline and Hazardous Material Safety Administration (PHMSA) regulatory impact analyses.

Our analysis has two main findings. First, air pollution and greenhouse gas costs are substantially larger for rail than for pipelines. For shipments of crude oil from North Dakota to the Gulf Coast in 2014, the air pollution costs and greenhouse gas costs are nearly twice as large for rail as for pipelines. Second, air pollution and greenhouse gas costs are much larger than spill and accidents costs. We find that air pollution and greenhouse gas costs are more than twice as big as spill and accident costs for rail and more than eight times as big for pipelines. Our findings indicate that the policy debate surrounding crude oil transportation has put too much relative weight on accidents and spills, while overlooking a far more serious source of external cost: air pollution and greenhouse gas emissions.

The comparisons between crude oil movements by rail and pipelines extend to other petroleum products.[1] In addition to transporting crude oil, the nation's rail system moves significant quantities of other petroleum products. These include processed petroleum products, propane, butane, isobutane, biodiesel and ethanol, all of which can be moved either by rail or by pipeline. Figure 1 shows data from the American Association of Railroads on the weekly numbers of carloads or intermodal units shipped of petroleum and petroleum products show that shipments fell from about 16,000 carloads per week in 2014 to slightly less than 10,000 carloads per week in 2017. Most of the decline is attributable to declines in the movement of crude oil after 2014. Thus, while declining crude oil prices have led rail shipments of crude to decline over the last 3 years, movements of other petroleum products still occur in significant quantities. Further, if crude oil prices rise again, movements of crude oil by rail may increase again as well.

2. Background

Figure 2 shows that oil production in the United States increased tremendously beginning in 2008. One driving factor was the rise of production in the Bakken Field, which is primarily located in North Dakota. As a result of this rapid increase in production, in 2014 North Dakota was the third largest producer of oil in the United States after Texas and the federal offshore region in the Gulf Coast.

Shippers send oil to the location that provides them with the largest revenue net of transportation cost (termed "netbacks"). Firms move oil to a rail or pipeline terminal

[1] The estimates will differ with the specifics of the pipelines used to move the products, but the qualitative findings will be similar.

using either truck or gathering pipelines.[2] Our analysis focuses on the long distance transportation of crude oil and excludes these 'first miles' primarily because of difficulties in obtaining detailed data on how oil was moved from the wellhead to a terminal. [3] Firms can ship crude oil to refineries using a range of modes of transportation, including rail, pipeline, or some combination of rail, pipeline and water. In this last case, oil is initially transported by rail or pipeline and is then offloaded to tankers or barges for shipment to refineries. In 2014, U.S. refineries reported receiving 78 percent of domestically produced crude oil by rail or pipeline.[4] They reported receiving the remaining 22 percent by tanker, barge, or truck.

Firms shipping crude oil from the Bakken are likely to use pipelines to the extent that there is available capacity, because rail is significantly costlier than pipeline per barrel-mile shipped. For example, Frittelli et al (2014, p. 7) noted that: "Railroad transport reportedly costs in the neighborhood of $10 to $15 per barrel compared with $5 per barrel for pipeline." This is consistent with information from Genscape, Petrorail Report (various dates). Additional oil is shipped by rail to the extent that it is economically attractive to do so. Shippers may also use rail, because it serves a more flexible set of destinations with faster delivery times relative to pipelines. Another factor in the continued use of rail – even when the economics appear unfavorable – is the fact that some shippers entered into multi-year contracts for rail shipments when the price of

[2] In aggregate, about 50 percent of oil was shipped from the wellhead by a gathering pipeline (North Dakota Pipeline Authority 2015). https://ndpipelines.files.wordpress.com/2012/04/kringstad-oil-gathering-slides-11-10-2015.pdf

[3] We have not been able to determine the extent to which trucking is correlated with moving crude oil by rail versus pipeline. If trucking for the `first mile' is positively correlated with subsequently moving crude oil by rail, this will increase the air pollution associated with rail. If trucking and crude-by-rail are negatively correlated, this will increase the air pollution from crude-by-pipeline. The Director of the North Dakota pipeline authority did not know whether the correlation was negative or positive [private correspondence].

[4] Authors' calculation based on Energy Information Administration (nd) data on Refinery Receipts of Crude Oil by Method of Transportation for 2014.

oil was high. These "take-or-pay" contracts require them to ship oil by railroad or pay for unused capacity.

Roughly half of the oil shipped from North Dakota in 2014 went to refineries by pipeline and the remainder went to refineries by rail. Of the 266 million barrels moved by pipeline from PADD2, which includes North Dakota, 1 percent moved to PADD1 (East Coast), 84 percent moved to PADD3 (Gulf coast) and 15 percent to PADD4 (Intermountain West). In addition, roughly 67 million barrels stayed within PADD2.[5] Most of the oil moving by pipeline ends up in the Gulf Coast or the Intermountain West, because there is almost no crude oil pipeline infrastructure on the East and West Coasts. Of the 250 million barrels moved by rail from PADD2 in 2014, 54 percent moved to PADD1 (East Coast), 21 percent moved to PADD3 (Gulf Coast), 21 percent moved to PADD5 (West Coast), and 4 percent moved to PADD4 (Intermountain West).

Pipelines, Railroads, and Crowd-Out

A central issue in North Dakota is the extent to which trains carrying crude oil crowd out the rail transportation of other products. When evaluating the air pollution effects of crowding out, it is helpful to think about the two ends of the spectrum. The first extreme is that railroads are operating with excess capacity and so additional rail traffic has no congestion externality on the rail system. In this case, any additional crude-by-rail traffic increases the overall air pollution costs from transporting goods by rail. The other end of the spectrum is that railroads are already operating at full capacity. In this

[5] Energy Information Administration (nd) data on Movements of Crude Oil and Selected Products by Rail. It is possible to back out approximate movements of oil by pipeline within PADD2 by taking total production in PADD2 and subtracting movements to other PADDs by all modes. Further, crude by rail is tracked within PADD2, so the residual is predominantly pipeline with some small share of water movement. Summarizing, our approximation (in thousand barrels) of the pipeline movements within PADD2 is calculated as follows: 67,000 = 616,000 (production) – 539,000 (shipments out of PADD2) – 10,000 (crude by rail movements within PADD2).

case, increased crude-by-rail traffic completely crowds out lower value products. There is no change in the total rail traffic due to crude-by-rail in this scenario, and thus there is no change in the overall air pollution costs from transporting goods by rail. In fact, the crowding out of other products may cause additional pollution, if these products are transported by other modes such as trucks instead. There are three possible sources of air pollution: i) railroad-related pollution from increases in rail traffic; ii) any additional pollution related to system-wide railroad congestion, since slower speeds are associated with higher fuel consumption; and iii) pollution stemming from products being shipped by other, more environmentally harmful modes of transportation (such as truck) rather than by rail.

North Dakota is heavily reliant on rail to move agricultural goods – 80% of grain was transported by rail in 2009 to 2012. Agricultural goods such as grain may be "time-shifted" rather than crowded out. Namely, higher tariff traffic such as crude oil may be moved first; other lower tariff traffic such as agriculture may be moved as capacity emerges. Rail capacity concerns materialized in 2013/14. The problem was particularly acute because of the record corn, soybean, and wheat harvests in that year.

If crude-by-rail crowded out the rail transportation of other goods, we would expect to see declines in agricultural shipments. Figure 3 shows the monthly total number of carloads originating in North Dakota, separately for oil, coal, and agricultural products. We remove seasonal trends in this figure by subtracting the month-of-the-year average total carloads of each good from the monthly observations. We smooth the resulting de-trended carloads' time series using the LOWESS method. This figure demonstrates that the (de-trended, smoothed) total number of carloads of crude oil shipped by rail from

North Dakota markedly increases over time. Consistent with railroads having excess capacity, we do not see a corresponding decrease in the number of carloads of coal or agricultural goods shipped. As USDA (2015) noted, despite producers' complaints exports of agricultural products also increased over this period.

Based on this evidence, we assume in our analysis that railroads are operating with excess capacity. In total, we are estimating a lower bound on the air pollution associated with transporting crude oil following the Bakken oil production boom, because: 1) emissions per ton-mile for alternative forms of transportation (such as trucks) are higher than for railroads, 2) we are ignoring rail congestion effects, and 3) as we will discuss further in section 3, our main estimates do not include idling, and 4) we ignore emissions associated with transport from wellheads to on-loading terminals.

3. Data

The Energy Information Administration (EIA) reports monthly and annual crude oil production for each U.S. state.[6] EIA also reports PADD to PADD movements of crude oil by mode of transportation, and the mode by which crude oil is delivered to refineries by refinery PADD.

We have data on the location of rail networks used to transport crude oil across the United States from the Center for Transportation Analysis at Oak Ridge.[7] Using GIS, we measured the number of miles of track in each county for all rail routes carrying high volumes of crude oil from North Dakota. Because many lines run along county

[6] Energy Information Administration (nd). Crude Oil Production, Monthly and Annual.
[7] Center for Transportation Analysis, Oak Ridge National Laboratory. (2009).

boundaries, we computed a one-mile wide buffer along each line and used the relative areas to allocate rail miles to counties.

Our analysis also draws on confidential waybill data for 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.[8] 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.[9]

Table 1a shows routes, route lengths, and barrels shipped across all waybills and by region. In 2014, trains transported roughly 214 million barrels of crude oil produced in North Dakota. We map and analyze over 95 percent of this crude-by-rail traffic over 41 distinct routes from North Dakota to refineries across the contiguous U.S.

We use data from Genscape, on the monthly flow of crude oil through each of the majority of major pipelines from the Bakken. Genscape (2014) also provides data on monthly electricity consumption at selected pumping stations for these pipelines. Finally, this database contains GIS information on pipelines and pumping stations. In 2014, Genscape monitored 68 percent of the overall volume of crude oil transported from North Dakota.

Table 1b shows distance between pumping stations, pumping station power consumption, pumping station oil flow and number of monitored stations by NERC region. In 2014, the average distance between pumping stations was 135 miles, power

[8] More detail on the STB's sampling procedure is provided in the following document: https://www.stb.dot.gov/stb/docs/Waybill/Waybill%20Sample%20Directions%20--%20Statement%2081-exp%206-17.1.pdf
[9] More detail on the STB waybill sample for 2014 is provided in the following document: http://www.stb.gov/stb/docs/Waybill/Revised%202014%20STB%20Waybill%20Reference%20Guide.pdf

consumption was 34,885 megawatt hours per year, and oil flow was 88,000,000 barrels per year. There are 404 monitored pumping stations.

4. Rail Cost per Ton Mile and per Hour for Idling

To calculate emission costs for rail we rely on four components: 1) gallons of diesel consumed, 2) the EPA locomotive emissions factors per gallon for a particular year, which are based on fleet composition for that year, 3) data on movements of crude oil to identify the location of emissions, and 4) the AP2 integrated assessment model, which links emissions to changes in air pollution and changes in air pollution to damages.

Diesel Consumed, Emission Factors, and Movements of Crude Oil

To calculate gallons of diesel consumed, we adopt an approach that distinguishes between outbound (loaded) trains and empty trains returning to North Dakota.[10] 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 oil) is transported one mile for each gallon of diesel fuel burned by the locomotive.[11] For return trains, we assume that the empty trains travel 0.14 miles per gallon of diesel consumed (U.S. Department of State, 2014).

We use EPA (2009) projected locomotive emission rates for 2014, which are based on projected fleetwide composition of locomotives. The emission rates for NO_x, SO_2, VOC, $PM_{2.5}$, and CO_2 are expressed in grams per gallon of diesel fuel consumed. Quantities of crude oil shipped from the STB waybill sample are used to calculate the number of barrel-miles for each county along the 41 routes. This allows us to compute

[10] Our approach is very similar to the approach used in the Environmental Impact Statement (EIS) conducted for the Keystone XL pipeline (United States Department of State, 2014).

[11] See United States Department of State (2014), Appendix Y and Association of American Railroads (2017).

emissions by county for movements of crude oil from North Dakota in 2014. We convert ton-miles of crude oil transported to gallons of diesel burned in each county. This is translated into emissions using locomotive emission factors for tier 2 locomotives. Because returning trains travel 0.14 miles per gallon of diesel consumed, converting emission rates is straightforward for empty trains.

One thing to note is that 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.[12] For example, unit trains take an average of 14 hours to travel through Chicago (CMAP, 2016). Because major junctions occur in urban areas, not accounting for idling and congestion will bias downward our estimates of emissions in urban areas and bias upward estimates of emissions in rural areas. As a result, our aggregate air pollution cost estimates are likely biased downward.

We separately estimate the emissions from trains sitting idle at: Chicago, East St. Louis, and Detroit. We estimate fuel consumption rates for trains switching in rail yards by capitalizing on the reported time (in hours) that trains spent switching and in yards from the STB. The STB also reports total fuel consumption while switching (STB, 2014). Combining fuel consumption with EPAs gram per gallon emission rates yields estimates of emissions per hour in rail yards.

AP2 Integrated Assessment Model

The AP2 integrated assessment model (Muller, 2014) uses an air transport model to link emissions in a specific county to changes in air pollution in every county in the

[12] Similarly, fuel consumption is higher if the grade on the route traveled is positive, so our estimates will understate emissions in counties with positive average grades and understate them elsewhere.

United States.[13] It then translates these changes in pollution into estimates of physical impacts by first calculating exposures. This step requires detailed population data provided by the U.S. Census.[14] Then, using peer reviewed concentration response functions, exposures are converted to physical effects: cases of illness, additional deaths. Finally, these impacts are monetized using standard non-market valuation techniques for human health consequences.

Most of the monetary damages are due to increased mortality risk and the social cost of carbon. For mortality risk, AP2 uses the Value of a Statistical Life (VSL) approach. In particular, the AP2 employs the EPA's VSL estimate of $8.5 million (2014 US dollars), which is standard in both the academic literature and in policy analyses (EPA, 2011). This VSL is the average of roughly 30 revealed and stated preference studies, each of which estimate 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 $43/ton (2014 US dollars), which is the social cost of carbon estimated by the U.S. government (IWGSCC, 2013).

The AP2 estimates marginal damages as follows. First, the model calculates the total damage associated with baseline emissions from all sources in 2011 (Muller and Mendelsohn, 2007; 2009). These damages are calculated using emissions, population, and vital statistics from 2014, which is the most recent year for which there are comprehensive emission inventories in the United States (Jaramillo and Muller, 2016). Then, one ton of one pollutant is added to one source. The model re-computes

[13] See Muller (2011) (especially Figure A2 in the supplemental material) and Jaramillo and Muller (2016) (especially the discussion in the appendix on pages 2 and 3) for evidence that the AP2 model correctly predicts monitor-level outcomes.

[14] The model calculates damages from human health effects as well as crop and timber yield loss, and materials depreciation. However, the vast majority of impacts are due to human health.

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, NH_3, and VOCs from roughly 10,000 ground-level and point sources in the United States. These exposures are translated into physical health effects using peer-reviewed concentration-response functions.

Importantly, the $/ton damage of pollutant (p) released from location (c) is a spatial sum of impacts over multiple counties that receive pollution (r) from a given source. Note that $D^{b}_{r,p,t}$ reflects the total damage in county (r) from pollutant (p) at time (t) due to the baseline level of emissions, while $D^{+1}_{r,p,t}$ is the total damage when an additional ton of pollutant (p) is added to the 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 accounts for the fact that these emissions disperse into nearby counties; the damages from the emissions from this locomotive calculated by AP2 occur in potentially many different nearby counties.

5. Pipeline Costs per Megawatt

To calculate emission costs for existing pipelines, we rely on three components: 1) the location and power draws of pumping stations in megawatt hours, 2) the Graff-

Zivin, Kotchen, Mansur (2014) model which translates electricity draws into powerplant emissions and 3) the AP2 integrated assessment model, which was described previously.

We use monthly, station-level electricity consumption and pipeline-level crude oil flows from Genscape (2014).[15] We then employ the method developed by Graff-Zivin, Kotchen, Mansur (2014) in order to link electricity 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). We use 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.[16] Emissions of pollutant (p) due to 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 that denotes whether power plant m increases its production in response to the electricity demanded at pumping station s. This indicator function varies both at the plant level as well as the NERC region level (based on the location of the

[15] Genscape monitors electricity consumption at 74 of the 404 pumping stations in our database. For remaining pumping stations, we know location, distance, and flow. We use the electricity demand reported for the monitored pumping stations as well as oil flows to estimate electricity consumption for unmonitored stations on the same pipeline.
[16] The United States Department of State (2014), Appendix Y Keystone XL analysis only considers CO_2 emissions from power plants because analysis of the emissions of criteria pollutants from power plants was not required for the purposes of the National Environmental Policy Review.

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.

6. Air Pollution and Greenhouse Gas Costs for Rail and Pipelines

Table 2 presents our estimates of the average air pollution and greenhouse costs per million barrel miles and per gallon for long distance transportation of crude oil from North Dakota to the Gulf Coast in 2014. Figure 4 plots the relative magnitudes per million barrel miles.[17] For movements to the Gulf, the sum of air pollution and greenhouse gas costs by rail, $1015, is nearly twice the costs by pipelines, $531. Air pollution damages were much larger for rail than for pipeline ($814 vs. $273). The greenhouse gas costs were somewhat smaller for rail than for pipelines ($201 vs. $257).

The air pollution costs per million barrel-miles are the highest for crude oil trains with destinations on the East Coast, $1,228, because these trains travel through more densely populated areas. Gulf Coast rail damages are $814, which is slightly lower than the sample average for rail but is much higher than the air pollution costs from pipelines of $297. The average damages are significantly lower for routes to the West Coast, $444. This is because trains headed to the West Coast typically do not pass through heavily populated areas such as Chicago or Philadelphia. Greenhouse gas damages are solely based on emissions and not on emissions and population density. As a result, they do not vary by region.

The air pollution and greenhouse gas damages per gallon differ across regions, because the distances traveled vary across routes. The average total damages per gallon

[17] For reference, one unit train with 100 cars carries approximately 75,000 barrels. The distance from western North Dakota to either St. James Louisiana or Philadelphia is about 1,970 miles. Moving the equivalent of one train over 1,970 miles is 148 million barrel-miles (75,000 barrels x 1970 miles).

of crude oil moved to the Gulf Coast are \$0.025 for pipelines and \$0.048 for rail. The average total costs for rail to the East Coast and West Coast are \$0.022 and \$0.065.

As we noted previously, estimates in Table 2 are lower bounds, because our main estimates do not include idling at the origin, destination, or the junctions and so are lower bounds. Table 1A presents estimates of damages per train hour and per gallon-hour for three major junctions – Chicago, East St. Louis, and Detroit. The costs on a per hour basis are high, because these are densely populated urban areas, so emissions affect large numbers of individuals. If a train to the East Coast spent one hour idling in Chicago, the air pollution and greenhouse gas costs per gallon would increase from \$0.065 with no idling to \$0.086 per gallon with one hour of idling.

Table 3 and Figure 5 present a more detailed pollutant-level comparison of the damages from crude oil transported by rail versus pipeline to the Gulf Coast. It is important to emphasize that the air pollution damages from pipelines are due to emissions in counties with power plants rather than counties with pipelines.

The top panel of Table 3 reports emissions per million-barrel-miles, and the bottom panel reports damages. Rail emissions are higher for NO_x and $PM_{2.5}$, while pipeline emissions are higher for SO_x and CO_2.

The starkest difference between rail and pipeline is for NO_x. Emissions of NO_x are 10-times greater for rail than for pipelines, while monetary damages from these NO_x emissions are 24-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.

It is worth noting that we are currently using 2011 emissions estimates for power generation. Relative damages are likely to have changed in a manner that suggests an even larger differential between rail and pipeline transportation of crude oil. For example, the eGRID database reports that the power generation fleet emitted 0.62 tons of CO_2/MWH in 2010. In contrast, in 2014, CO_2 emission intensity is estimated at 0.56 tons/MWH. Even more strikingly is the reduction in SO_2 emissions; in 2010 the emissions rate across all plants was 0.0013 tons/MWH whereas in 2014 this rate was 0.0008 tons/MWH. Considering that CO_2 and SO_2 emissions at power plants comprise the bulk of damages from pipeline transport, it is likely that crude-by-rail is even more harmful, relative to pipelines, today.

The total estimated damages for oil shipped by rail from North Dakota in 2014 are greater than $420 million. According to the National Research Council of the National Academies of Science (NRC), this is more than twice the damage done by the average coal-fired power plant, annually (NRC, 2010). Our analysis suggests that about 30 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 and timber production, and accelerated depreciation of man-made materials.

Our work is related to estimates of the pollution attributable to the *combustion* of gasoline and diesel. The NRC (2010) estimated air pollution damages of between $0.23/gallon and $0.38/gallon, in $2007, for 2005 model year autos, trucks, sport utility vehicles, and light trucks burning gasoline.[18] We report that the external costs associated with *transporting* one gallon of crude oil averages $0.047 across all of our modeled rail routes. Thus, the external costs of long distance transportation of a gallon of crude oil by rail are between 10 and 20 percent of the costs of burning a gallon of gasoline or diesel. As penetration of pollution control technology in the vehicle fleet continues, damages per gallon will fall. However, population growth puts upward pressure on per-gallon social costs. The pollution costs of both transporting and burning motor fuels are essential for a life cycle analysis of the consumption of these fuels.

7. Spill and Accident Costs for Rail and Pipelines

The Pipelines Hazardous Materials Administration (PHMSA) conducted a regulatory impact analysis (RIA) on Enhanced Tank Car Standards and Operational Controls for High-Hazard Flammable Trains in 2015 (PHMSA (2015)). In particular, this RIA developed estimates for crude oil and ethanol of the cost of spills and accidents per carload, which include property damage, cleanup costs, injury costs and mortality costs. PHMSA (2015) presents a range of social costs that can be translated into barrel-miles using information on carloads, barrels per carload, and average distance. [19]

[18] See NRC (2010), p. 11 footnote 10. For light-duty vehicles from the late 1990s, Parry, Walls, and Harrington (2007) estimates air pollution damages of $0.52/gallon.

[19] PHMSA (2015) Table EB14, p. 111. Carloads are from p. 82 of PHMSA (2015), distance traveled is from p. 200 of PHMSA (2015), and barrels per carload are from Energy Information Administration (2013). Average distance for oil originating in the Bakken is 1,098 miles. The costs are not reported separately for crude oil and ethanol, but the average cost per gallon used in the estimates ($200) is only slightly less than the estimate for crude oil spills, ($211).

Translated into costs using information on carloads, barrels per carload, and average distance, these estimates range from $214 per million-barrel miles at the low end to $966 per million-barrel miles at the 95th percentile; with a median estimate of $381 per million-barrel miles. There is a high level of uncertainty in these estimates, because the probability of a very high cost event, such as a crude oil train explosion near a populated area, is difficult to determine.

PHMSA's (2015) preliminary regulatory impact analysis 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."[20] For hazardous liquids, high consequence areas (HCAs) "include populated areas, drinking water sources, and unusually sensitive ecological areas."[21] Forty-three percent of pipeline miles are in HCA. The annual social costs of spills and accidents 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 to be lower bounds of true social costs of spills and accidents due to crude-by-pipeline.[22] We next translate PHMSA's social costs from dollars per mile to dollars per barrel-mile for crude oil, with the caveat that PHMSA's numbers are not calculated separately by product

[20] Econometrica (2015) p. 15.
[21] Econometrica (2015) p. 1.
[22] From Econometrica (2015) p. 19: "there are important social costs completely missing from the estimates and some costs that are likely underestimates of the true social costs."

type.[23,24] The estimated cost of spills and accidents per million-barrel miles of crude-by-pipeline is roughly $62.

The majority of policy concern regarding movements of crude oil by rail and pipeline has focused on the costs associated with accidents and spills. As noted above, PHMSA's central estimates of the costs from spills and accidents for rail and pipelines is $381 and $62 per million-barrel miles. Firms and insurers pay a share of these costs and the remainder is an externality. However, even if firms did not internalize any of these costs, Figure 6 suggests that the total air pollution and greenhouse gas costs for rail and pipelines to the Gulf Coast are far larger than PHMSA's spills and accidents cost estimates ($1015 vs. $381 for rail; $531 vs. $62 for pipelines). Summarizing, policymakers should consider both the costs from air pollution as well as spills and accidents when calculating the total social costs of moving crude oil to refineries.

8. Conclusion

This analysis uses data on crude oil transportation from North Dakota in 2014 to examine the relative air pollution, greenhouse gas, and spill and accident costs for movements of petroleum products by rail and pipelines. We find that total air pollution and greenhouse gas costs are substantially larger for rail than for pipelines. Further, for both rail and pipelines, the sum of air pollution and greenhouse gas costs is substantially larger than spill and accidents costs. These results suggest that the policy debate surrounding crude oil transportation has put too much relative weight on accidents and

[23] Econometrica (2015) Appendix A, which lists preventable incidents that occurred during 2010-2014, 12 of the 20 highest cost incidents involved crude oil.
[24] Smith, Christopher (2014), appendix. Computing the weighted average cost for the HCA and non-HCA pipelines yields a social cost per pipeline mile for crude oil of $1,552. $62 per million barrel miles = (150,609 miles x $1552 /mile)/3,799,753 million barrel miles.

spills, while overlooking a far more serious source of external cost: air pollution and greenhouse gas emissions.

The air pollution and greenhouse gas damages are large. For example, air pollution and greenhouse gas costs of moving a fully loaded 100-car train of crude oil from North Dakota to the Gulf Coast are about $150,000 and from North Dakota to the East Coast are $210,000. The air pollution and greenhouse gas costs of moving an equivalent amount of oil by pipeline to the Gulf Coast are $78,000. The total estimated air pollution and greenhouse gas damages for oil shipped by rail from North Dakota in 2014 exceed $420 million. As we noted, our estimates are a lower bound, in part because we assume a train does not idle. Idling, particularly in major junction cities such as Chicago, is very costly.

While the recent downward trend in crude prices has led to marked reductions in the movement of crude oil, other petroleum products continue to be moved by rail in large volumes. The issue of the relative costs of moving these products by rail and pipelines extends to those products as well. The air pollution and greenhouse gas costs of transporting different petroleum products will vary with the characteristics of the product and the pipeline. The results presented here suggest that further research on the air pollution and greenhouse gas costs of transporting these products is necessary.

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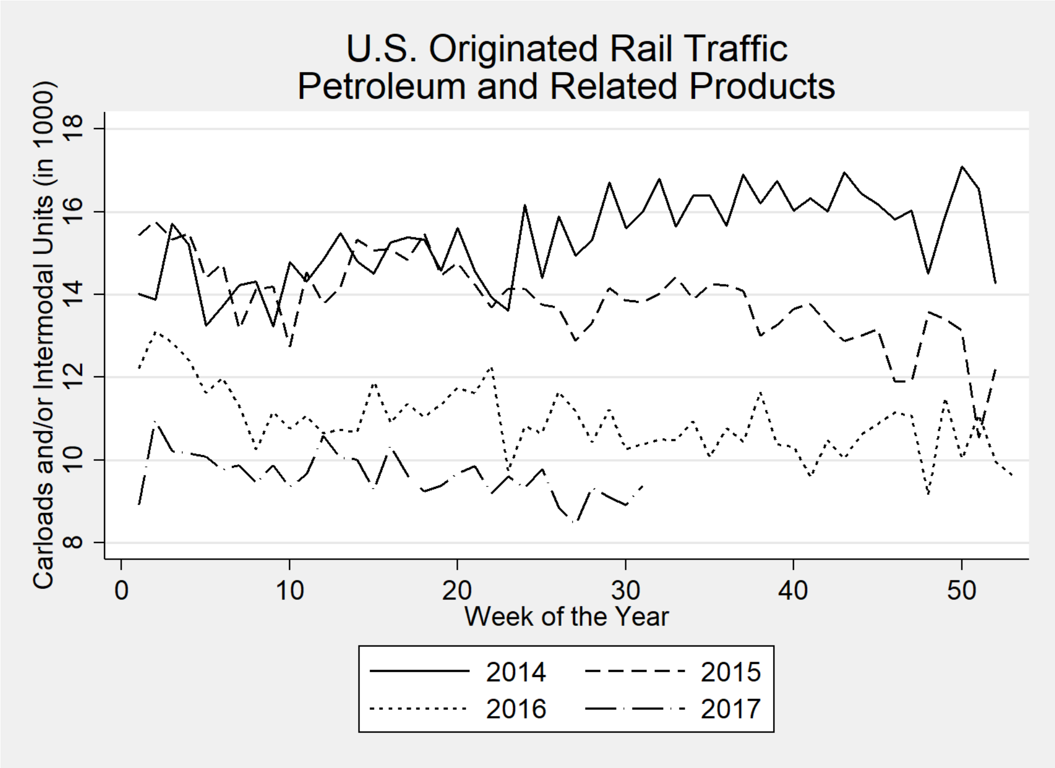
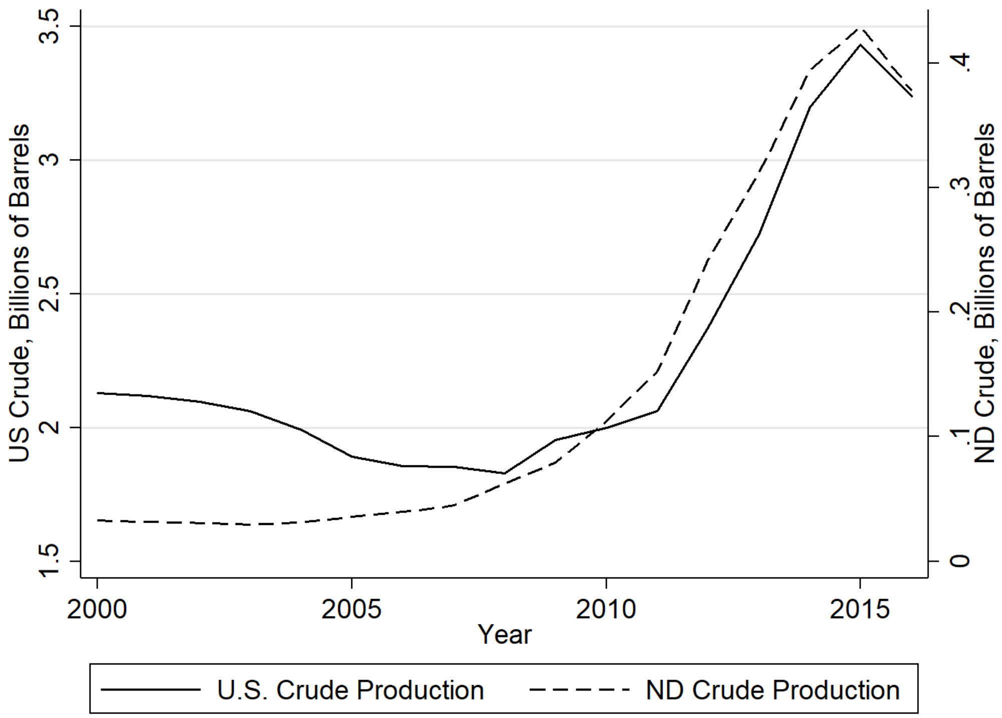
Figure 1: Movements of Petroleum and Petroleum Products by Rail in the United States 2014 to mid-2017



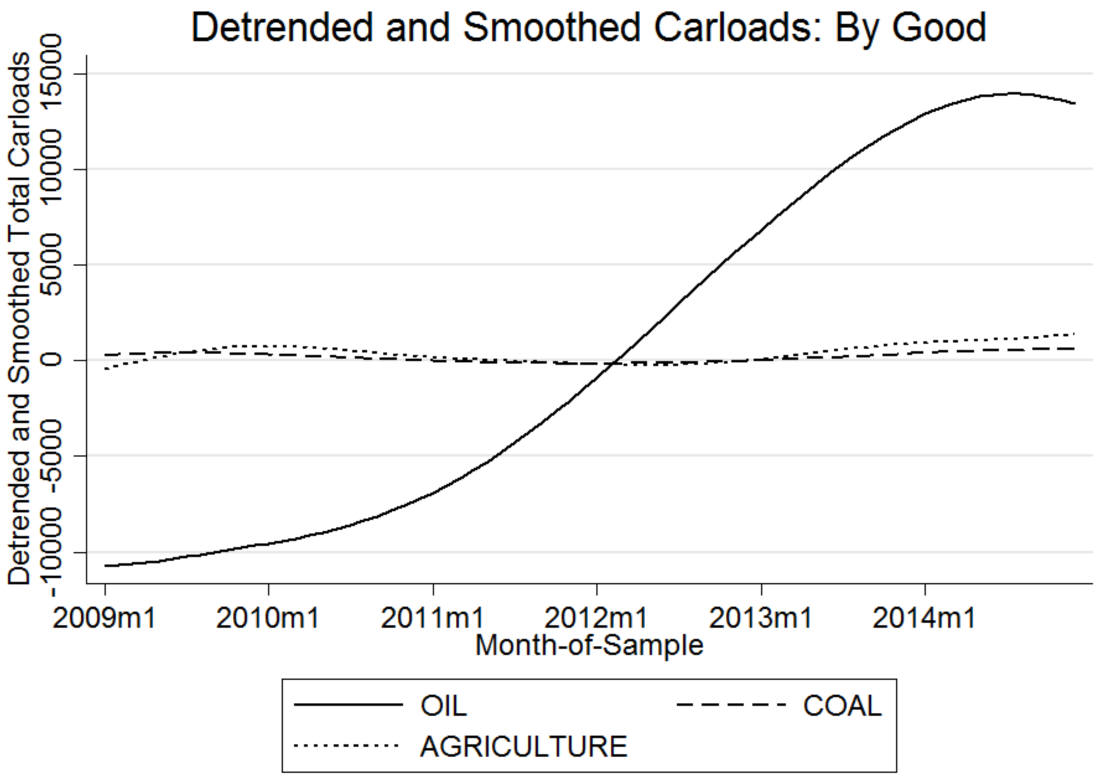
Notes: Weekly Rail Traffic for Petroleum and Petroleum Products are from Association of American Railroads: https://www.aar.org/data-center/rail-traffic-data

Figure 2: Crude Oil Production in the United States and Crude Oil Production in North Dakota



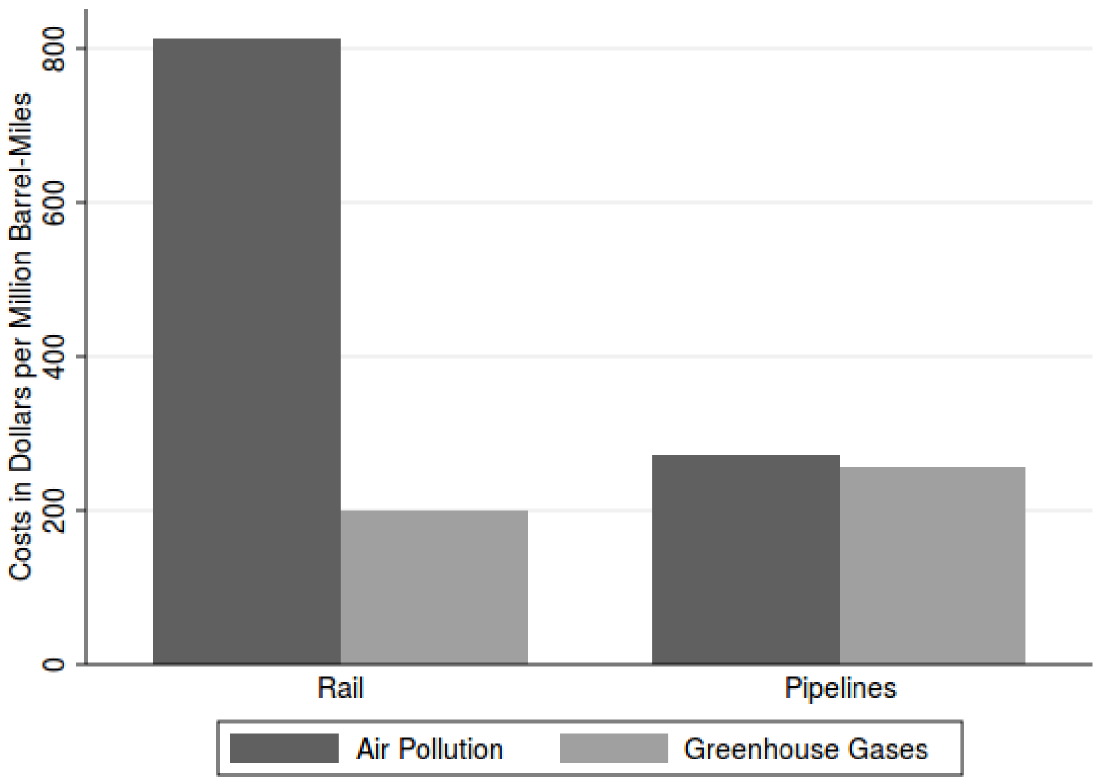
Notes: United States and North Dakota crude oil production are from Energy Information Administration (nd). Crude Oil Production, Annual.

Figure 3: Monthly Rail Waybills by Commodity Group Originating in North Dakota



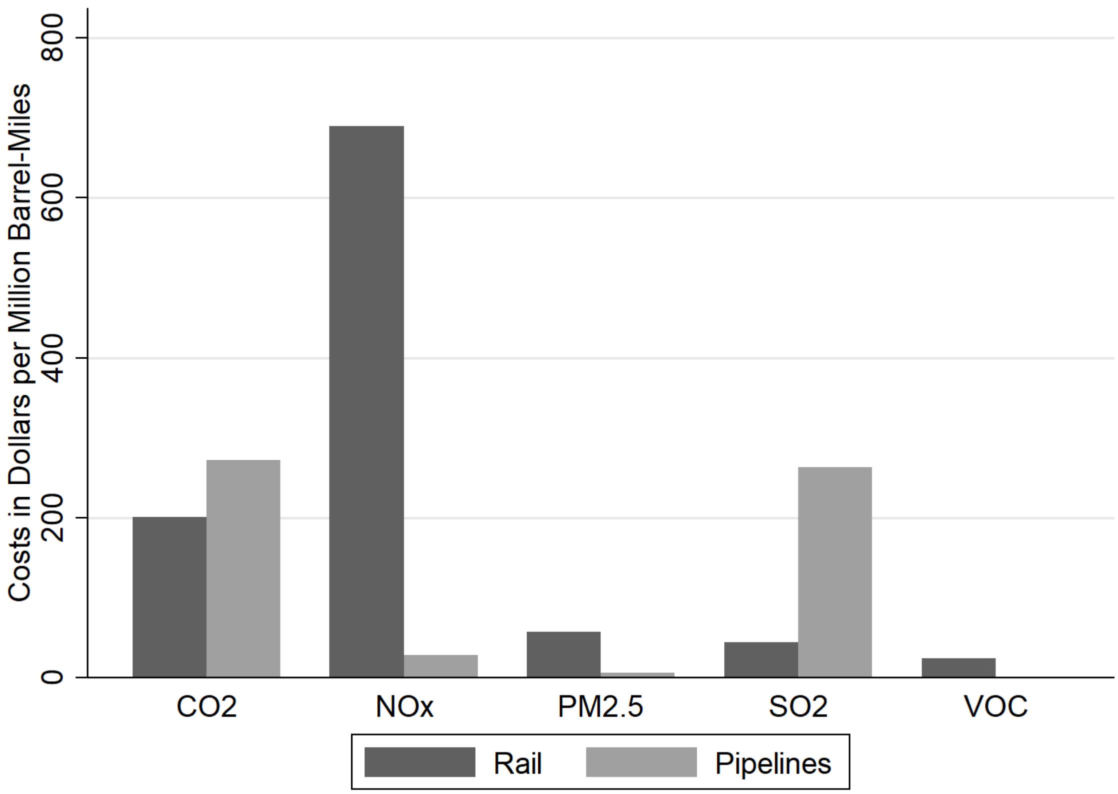
Notes: Based on STB Confidential Waybill Sample.

Figure 4: Air Pollution and Greenhouse Gas Damages for Transportation by Railroad and Pipelines to the Gulf Coast



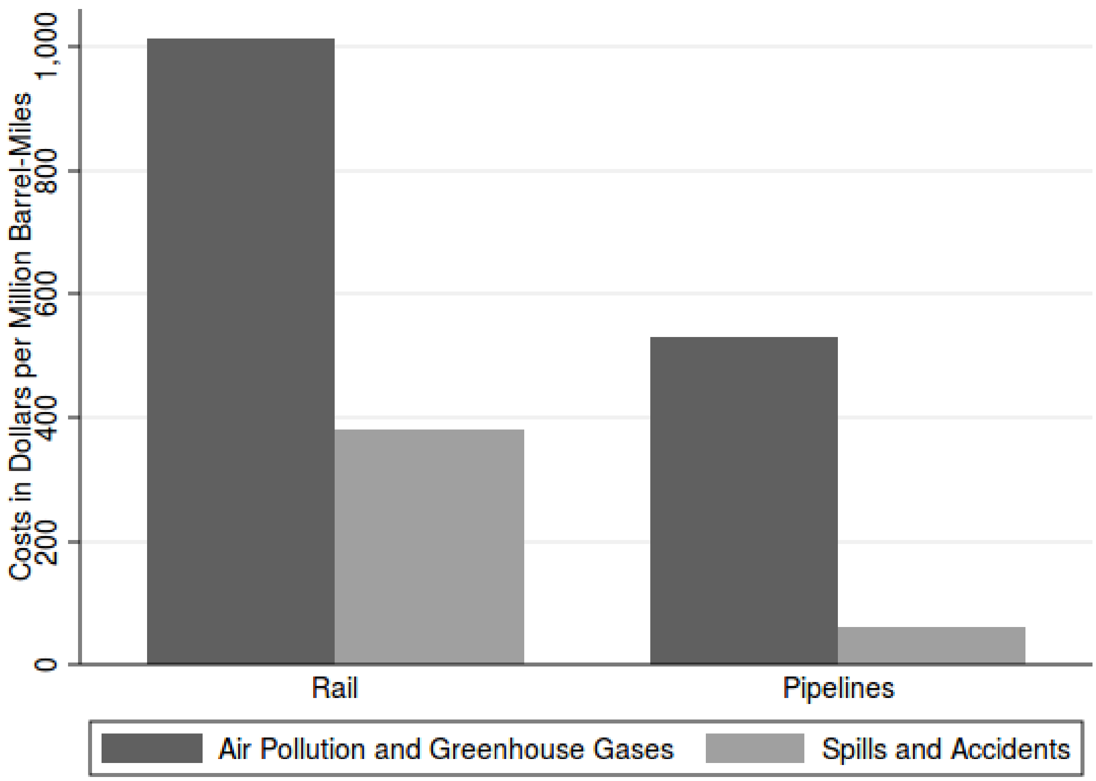
Notes: Data are from the first two columns of the upper panel of Table 2.

Figure 5: Air Pollution and Greenhouse Gas Damages for Transportation by Railroad and Pipelines to the Gulf Coast by Pollutant



Notes: Data are from the first two columns of the lower panel of Table 3.

Figure 6: Air Pollution and Greenhouse Gas Damages and Spill and Accident Costs for Transportation of Crude Oil by Railroad and Pipelines to the Gulf Coast



Notes: Data on air pollution and greenhouse gases are from the first two columns of the upper panel of Table 2. Data on spills and accidents are from calculations in the text.

Table 1a: Summary Statistics for Movements of Crude Oil by Rail

Destination	Number of Routes	Length Of Route (Miles)	Barrels Shipped
All Observed Waybills	41[B]	1,673.40 (388.18)	4,974,439 (4,974,439)
Gulf Coast	10	1,905.81 (301.21)	5,368,685 (6,392,663)
East Coast	16	1,910.16 (123.62)	5,726,865 (5,451,718)
West Coast	9	1,360.21 (290.22)	4,622,325 (5,311,929)

Notes: Movement of crude oil from North Dakota in 2014. A = Standard Deviations in parentheses. B = The number of routes from East Coast + Gulf Coast + West Coast does not equal 41 because some routes end either in the Midwest or Ontario.

Table 1b: Summary Statistics for Movements of Crude Oil by Pipeline

NERC Region	Distance between pumping stations (Miles)	Power Consump-tion (megawatt hours/yr.)	Oil Flow (million barrels/yr.)	Number of Monitors
MRO	160.04	68,237.9	142.2	65
RFC	277.14	23,726.0	104.9	32
SERC	109.33	23,785.1	77.0	83
SPP	130.58	21,793.6	55.9	126
TRE	75.97	31,560.1	104.7	41
WECC	111.31	50,609.3	92.0	57
All	134.94	34,885.0	88.0	404

Notes: Crude oil pipeline data for 2014 from Genscape (2014).

Table 2: Air Pollution and Greenhouse Gas Damages for Transportation of Crude Oil by Railroad and Pipeline from North Dakota to Refineries

	Pipeline-Gulf	**Rail-Gulf Coast**	**Rail-East Coast**	**Rail-West Coast**	**All Rail**
		($) Per million barrel miles			
Total	*530.64*	*1014.72*	*1428.80*	*644.86*	*1142.93*
Air Pollution	273.33	814.03	1,228.11	444.17	942.24
Greenhouse Gas Damages	257.31	200.69	200.69	200.69	200.69
		($) Per gallon of crude oil			
Total	*0.025*	*0.048*	*0.065*	*0.022*	*0.047*
Air Pollution	0.012	0.037	0.056	0.015	0.039
Greenhouse Gas Damages	0.012	0.009	0.009	0.007	0.008

Table 3: Air Pollution and Greenhouse Gas Emissions and Damages by Pollutant

Pollutant	Pipeline-Gulf Coast	Rail-Gulf Coast	Rail-East Coast	Rail-West Coast
Emissions (tons) per million barrel miles				
NO_x	0.005	0.061	0.061	0.061
SO_x	0.009	0.001	0.001	0.001
$PM_{2.5}$	0.001	0.002	0.002	0.002
VOC	*	0.003	0.003	0.003
CO_2	5.366	4.578	4.578	4.578
Damages ($) per million barrel miles				
NO_x	26.01	689.31	956.01	370.22
SO_x	240.73	44.28	81.60	25.61
$PM_{2.5}$	6.59	56.57	138.25	30.72
VOC	*	23.87	52.25	17.62
CO_2	257.31	200.69	200.69	200.69

Appendix

The equation for the estimation of the emission rates in tons per county is given by the following formula in which county is denoted (c) and pollutant (p):

$$E_{p,c} = D_c\left(\frac{miles}{county}\right) \times 0.14259\left(\frac{tons}{bbl.}\right) \times \left(\frac{bbl.}{train}\right) \times \left(480\,\frac{ton-miles.}{gal}\right)^{-1} \times E_p\left(\frac{grams}{gal.}\right) \times \left(\frac{tons}{9.07\ x\ 10^5\ grams}\right)$$

We estimate damages by county because the ($/ton) marginal damages are calculated by AP2 at the county level. Damages are then aggregated across all counties with a route. Finally, we divide damages by barrel-miles, by route, and scale up by 1,000,000 to compute damages per million barrel-miles.

Table 1A: Air Pollution and Greenhouse Gas Damages from Idling by Pollutant and Junction

Pollutant	Chicago	East St. Louis	Detroit	All Junctions
		Damages ($) per train-hour		
All	*1,379.05*	*674.46*	*870.29*	*1,198.95*
NO_x	962.49	514.91	576.58	846.57
SO_x	37.53	18.54	28.37	32.79
$PM_{2.5}$	231.42	46.62	131.53	184.99
VOC	69.97	16.75	56.17	56.96
CO_2	77.64	77.64	77.64	77.64
		Damages ($) per barrel-hour		
All	*0.0212*	*0.0092*	*0.0151*	*0.0182*
NO_x	0.0148	0.0070	0.0100	0.0128
SO_x	0.0006	0.0003	0.0005	0.0005
$PM_{2.5}$	0.0036	0.0006	0.0023	0.0028
VOC	0.0011	0.0002	0.0010	0.0009
CO_2	0.0012	0.0011	0.0013	0.0012