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Mitigating Environmental and Public-Safety Risks of United States Crude-by-Rail Transport

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IMPRESSUM

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<http://www.diw.de>

ISSN electronic edition 1619-4535

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Mitigating environmental and public-safety risks of United States crude-by-rail transport

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Abstract

We present a medium-term market equilibrium model of the North American crude oil sector via which we develop a scenario analysis to investigate strategies to mitigate the environmental and public-safety risks from crude-by-rail transportation across the United States. The model captures crude oil movements across railroads, pipelines and waterways, while distinguishing between light and heavy crude qualities. We find that restricting rail loads or increasing pipeline capacity from areas driving production will significantly reduce rail movements. However, lifting the United States crude oil export ban in isolation will only increase rail transportation volumes. We show that an integrated policy of targeted rail caps, pipeline investments and lifting the export ban sustainably addresses medium-term crude-by-rail risks in the United States.

JEL codes: Q31, Q38, L71, C61, C72

Keywords: crude-by-rail, market equilibrium, mixed complementarity problem, transportation capacity, infrastructure investment

1 Introduction

The United States experienced a major upsurge in the production of crude oil and natural gas over the past decade. This has been largely attributed to the advancement in drilling technologies (namely hydraulic fracturing, or “fracking”) that has made it commercially viable to exploit hydrocarbons in tight shale formations. The impact of this technology on the US and global natural gas markets has been extensively studied [1, 2] but economic-engineering modeling of the crude oil sector has received less attention in the academic literature so far. The epicenter of the shale oil revolution can be found in the Bakken formation (North Dakota), with significant contributions from the Permian Basin (Texas, New Mexico) [3]. Kilian [4] provides a comprehensive background on the effects of this “shale revolution” on prices and infrastructure in the US. Heavy oil production has also been expanding across North America, particularly in Canada [5, 6]. Investments in transport infrastructure, especially pipelines, have not kept up with the ramped up pace of production. The rail network has thus filled this void. It has also come under increased pressure as production in the oil sands of Western Canada has been on the rise, and Canadian exports to the US via rail nearly quadrupled from 46 kbpd (thousand barrels per day) in 2012 to 161 kbpd in 2014 [7]. A major consequence of the increased demand on rail infrastructure has been the rise of crude oil accidents. While pipelines do spill more gallons per incident, crude-by-rail spills have had more devastating impacts, as the rail lines often run next to rivers or through densely populated areas.

In order to better understand the North American crude oil market and provide policy recommendations toward mitigating the crude-by-rail problem, we have developed a medium-term equilibrium model that enables us to study the flow of oil from the fields to the refineries across the various modes of transportation in North America. The following are the scenarios we have designed to aid the investigation: restricting rail loading and flows, pipeline investments, the lifting of the US export ban on crude oil, and a combined implementation of these three policies. The producers and consumers (refiners) are Eastern and Western Canada, Mexico considered as a single entity, and the states that make up 95% of the US crude oil market. The time periods considered in this model are 2012, 2015 and 2018. To account for differences in crude oil qualities, we consider

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light-sweet and heavy-crude oil types. The implications of this differentiation are significant as refining and transportation capacities depend on the quality of the crude.

Over the past several decades, several models have been built to study the global oil market, often with a view to understanding price movements and impacts. In 1974, Kennedy [8] published a global oil model incorporating all sectors from the producers to the end-users, but with a focus on prices and tax effects. Krichene [9] developed a crude oil and natural gas model (2002) that served as a historical analysis of the global market from 1918 to 1999. More recently, a Global Oil Trade Model was constructed by Alkathiri et al. [10], which they used to explore the impact of supplier diversification on oil importer profits. Huppmann and Holz [11] presented a numerical Stackelberg Nash-Cournot partial-equilibrium numerical model to investigate the global crude oil market. Their single-period model was structured as a mixed complementarity problem, and it accounted for pool market behavior by ensuring price equivalence within specified demand hubs. Kilian [4] provides a detailed assessment of the current production boom in the US crude oil industry, particularly with regard to prices and infrastructure. Most recently, Langer et al. [12] have developed a partial-equilibrium model that details refining technologies and explores the global impact of lifting the US crude oil export ban.

Notably, Uri and Boyd [13] developed a linear model for the US oil market in order to examine the effects of price on imports. However, no modeling attempt with multimodal flow granularity and distinction by crude quality in the North American oil market currently exists in the academic literature. This paper presents a step toward filling this void: we simulate the resulting market equilibria under a range of different policy measures over the medium term, and the detailed engineering-economic model allows us to track crude oil movements by mode and at a spatial disaggregation level of US states. The transportation modes we consider are the waterways, railways and the pipeline network. A major effort in the development of this model, besides data gathering, went into calibrating the parameters, including costs of production, investments and transportation, in order to obtain valid results. As new crude-by-rail regulation and pipeline projects are being proposed to improve the infrastructure level of service as well as reduce the environmental impact of the crude oil industry from production to refining or export, our model can serve as a viable testing ground for a counterfactual scenario assessment of the impacts of these measures.

2 Model description

The model presented here has been built on a partial-equilibrium framework, *Multimod*, developed by Huppmann and Egging [14] to analyze the global energy market. It incorporates endogenous investments and fuel substitution, Nash-Cournot market power, storage operations, and seasonal variability.

In this adaptation, we are concerned with granularity within the US and interactions within the North American market. The players therein are restricted to the suppliers, which are synonymous with the producing nodes, and independent arc operators. We do not consider storage operators and transformation operators, as we limit consumption to the refining industry and do not include a further representation along the downstream value chain. We have also assumed perfect competition and, as such, the suppliers always exhibit profit-taking behavior. There are 14 supply nodes in the model, 10 of which are US states. Eastern Canada, Western Canada, Mexico and “Rest of the World” (RW) are the remaining four. All the aforementioned states are also included as consumers, with the addition of 14 other states within the US. The following sections describe the model and relevant parameters in the data initialization process.¹

2.1 Model implementation

Complementarity modeling has grown in importance owing to its ability to capture the complex interactions in energy markets. Mixed complementarity problems (MCPs) generalize equilibria and nonlinear programs, and they can be solved by a variety of Newton-based methods. In a competitive marketplace, each player’s optimization problem can be expressed as a set of Karush-Kuhn-Tucker (KKT) equations. The concatenation of the KKT conditions yields an MCP, and the solution to this system of equations is a market equilibrium of the underlying non-cooperative game.

We consider the North American crude oil market within an MCP framework, with the KKT conditions formulated from the optimization problems of the suppliers, the arc operators and the demand sector. The program is in GAMS, a high-level modeling language.² Data initialization, variable declarations and parameter assignments make up the first step. An algorithm is then called to reduce the size of the problem by excluding extraneous variables. As a feasibility check (to ensure total demand can be met), the program solves an overall cost minimization problem, and initial points for the supply prices are assigned from the solution. An automated iterative calibration algorithm is then run in order to match consumption at all nodes to reference levels, manipulating the end-use cost parameters in the process.

¹A complete mathematical formulation of the model is given in the Supplementary Information ([Appendix A](#)).

²General Algebraic Modeling Systems (GAMS), release 23.9.5; GAMS Development Corporation, <https://www.gams.com/>.

The program utilizes the PATH solver [15] to obtain an equilibrium to the non-cooperative game between market participants. We manually calibrate the model parameters such that the results coincide with reference production and regional transportation quantities for the base year (2012) and subsequent projected years (2015, in part, and 2018). This process is nontrivial, as it requires the adjustment of costs, both for production and transportation.

3 Data collection and methods

Data on US crude oil production and consumption (refining) were obtained from the EIA [16]. Domestic supply and demand projections are given by the EIA’s Annual Energy Outlook 2015 [17]. Similar data for Canada were obtained both from the NEB [18] and CAPP [19]. Global supply and demand quantities and projections, including those for Mexico, were obtained from the International Energy Statistics on petroleum compiled by the EIA [20]. The EIA also annually tracks regional crude movements across the country (and to and from Canada) by barge, rail and pipeline. However, further information on pipeline and rail loading capacities were only available from private sources. A list of all the nodes and arcs in model are given in the Supplementary Information (Appendix A). We selected 2012 as the base year, as this was when rail movements of crude oil across the continent first rose to prominence after the oil boom.

3.1 Crude oil production

The US has been a dominant player in the global crude oil market for many decades [3]. Production peaked in the 1970s, and the subsequent decline persisted until 2009 (see Figure 3A). The decline was a result of various factors: the institution of the crude oil export ban in 1978, the availability of cheaper oil from external suppliers and the increasing costs of domestic production. Canada also historically relied on the US to export its oil to other markets [21]. Over time the industry in the US converged to a market equilibrium under these conditions. Major refineries invested in technologies to improve capacity for the medium-heavy oil being imported from the Gulf States. The shale oil boom has again repositioned the US as a major oil producer, but challenges have arisen in terms of refining and transporting this additional volume, which is of the light-sweet variety [4, 22].

Western Canada is also an influential player, its growth primarily driven by heavy oil exploited from the sands of Alberta. Much of this oil finds its way down to the Gulf of Mexico for refining or export. Eastern Canada predominantly produces light crude. It also supplies some refiners along the East Coast of the US, while receiving shipments from Western Canada as well.

Mexico’s crude oil production industry is run by the state-owned Petróleos Mexicanos (Pemex)³ [23, 24]. Mexico is a net exporter of crude, producing close to 3 mbpd (million barrels per day) in 2012, and consuming only about half (for refining). However, it has to import refined gasoline to satisfy domestic demand [23]. The US is a major destination for Mexican crude, of which over 50% is of the heavy-sour grade [24, 25].

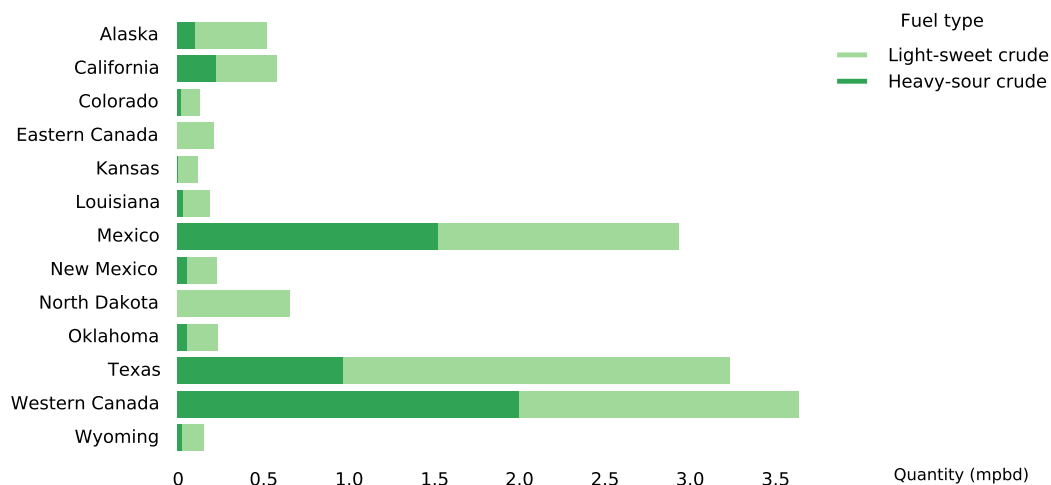


Figure 1: Production (supply) nodes, showing split between light-sweet and heavy-sour crudes

We considered the states that account for 95% of total US output. Estimates of light-to-heavy yield ratios were made based on industry reports and other surveys. Offshore production in the Gulf of Mexico was attributed to Texas, and California production also accounts for that off the southwestern coast of the US. In

³Since 2013, Pemex has been in transition to involve private participation for better performance in the industry [23].

2012, North Dakota and Texas were the fastest growing crude oil suppliers in the country [26]. Figure 1 shows the 2012 quantities for the suppliers. Production for RW was excluded from this diagram for clarity.

3.2 Refining and demand

The US currently must refine or store all its domestically produced crude oil. Many of the US refineries are situated next to waterways or in close proximity to the production fields. Canada refines some of its oil and exports to the US much of the remainder. Mexico is a net exporter of crude, shipping heavy oil to the US and to the global market. The US therefore has the largest refining capacity on the continent.

We consider demand as crude oil refining for the purposes of this model. Refining capacities for the US are available from the EIA, as are estimated utility rates. From these, we can obtain the quantities of crude oil consumed at the nodes of interest. Data on API gravity averages of crude oil inputs to refineries enable us to calculate yield rates for light and, consequently, heavy crudes. For Canada, the relevant data were obtained from the Canadian Fuels Association [27].

The demand quantities at each node are show in Figure 2 for the base year 2012. The quantity for RW is again excluded here for clarity.

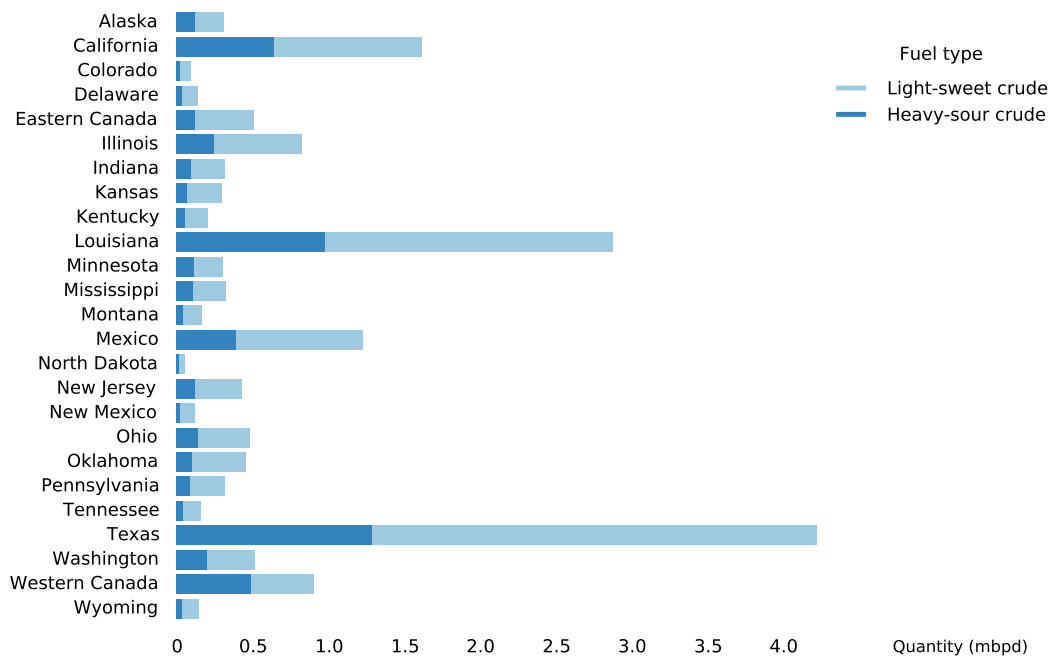


Figure 2: Refining (demand) nodes, indicating yield of light-sweet crude to heavy-sour crude

3.3 Transportation

The transfer of crude oil from the oil fields and production sites to refiners both within and outside North America occurs via land and water bodies. On land, pipelines, trains and trucks are used to transport crude. We do not consider the share of truckage, as it is insignificant compared to the other two. On water, tankers ply the sea routes while barges transport crude along the river system, of which the Mississippi is the most important. Intermodal exchanges also occur at certain nodes, e.g. rail to barge, tanker to pipeline, and so forth. In the following subsections, we outline the data collection process for the arcs in each mode, while providing a context for their importance in the market.

3.3.1 Railway

As discussed earlier, crude oil producers both in Canada and the US have become increasingly reliant on trains to move oil to the refineries (Figure 3B). All the production and consumption nodes, except for Alaska and Mexico, were considered as loading and unloading points for rail crude oil loads. Auxiliary rail nodes were then modeled at these points and in the intervening US states. Initially, all arcs connecting auxiliary rail nodes were assigned unconstrained capacities, while the loading and unloading arcs were constrained. During calibration, some auxiliary arcs were constrained in order to obtain base-case flows matching closely to observed reference values.

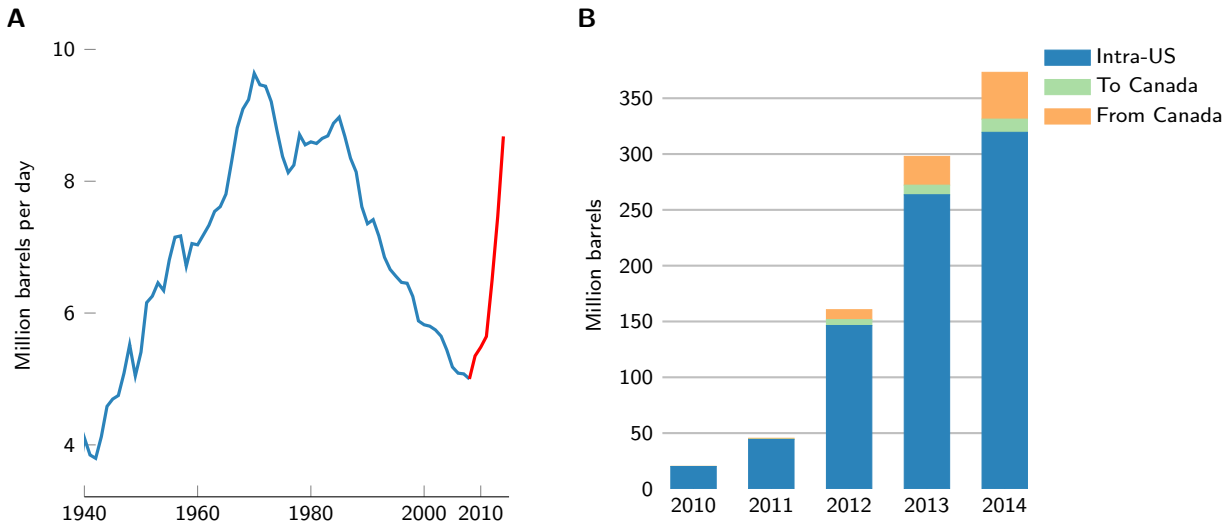


Figure 3: (A) US crude oil field production. (B) Rail movements of US crude (Source: EIA)

The rail capacity data were obtained from a myriad of industry publications,⁴ as compiled by Oil Change International [28] and providing the unloading and loading capacities of crude oil facilities in the US and Canada. We aggregated the loading and unloading capacities for each of the regions under consideration. Some of the facilities were operational but had no listed capacities. The missing data were filled using average capacities of the facility type. The scope of the rail network considered for the model is shown in Figure 4.

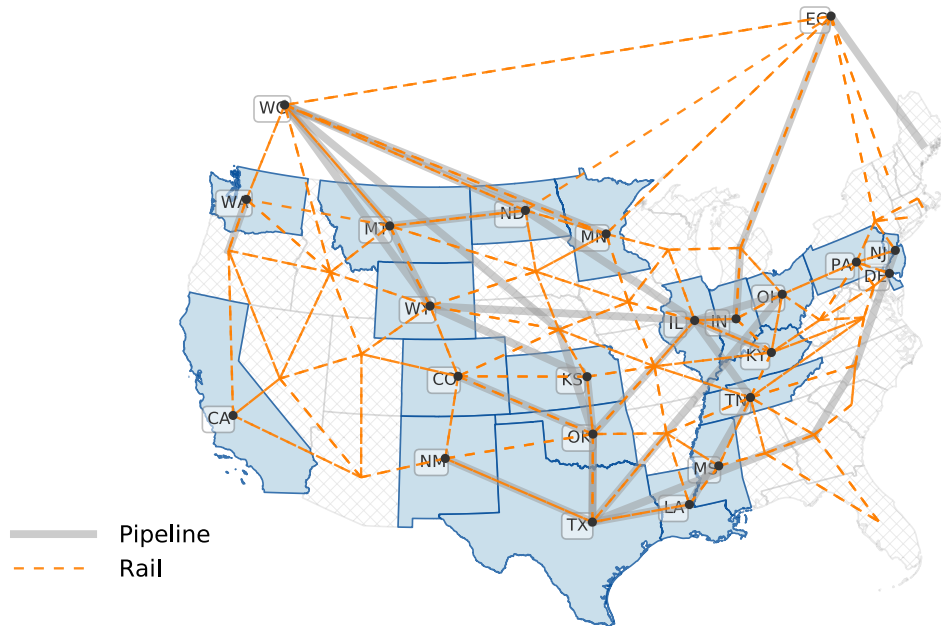


Figure 4: Map of internodal rail and pipeline arcs in the model (not indicating directionality). The US states labeled are production or demand nodes in the model.

3.3.2 Pipelines

Historically, the crude oil pipeline network in the US and Canada developed to transport oil from Canada toward the Gulf of Mexico, while capacity was increased within the Gulf region itself to facilitate movement between storage and refining facilities. Cushing, Oklahoma, became established as a trading and storage hub for both Canada and the US. In 2012, operators delivered over 20 mbpd of crude oil via pipeline in the US. This value increased by 11.3% in 2013 [29]. The rate of increase in pipeline delivery in 2014 was also identical at 11.6% [30]. On average, pipelines have consistently accounted for 80% of the modes share in crude oil transportation in the US since 2000 [31]. They are therefore a vital part of the crude oil infrastructure.

⁴These include: RBN Energy, Hart Energy, Genscape, BNSF, Canadian Pacific, Canadian National, Meritage Midstream, Howard Energy Partners, and Rangeland Energy

The process for gathering pipeline data began by consulting maps of established and functioning pipelines [19, 32] Most of the major pipelines in the US and Canada are owned by various private corporations.⁵ Excluding intranodal pipelines, capacity data were compiled for each internodal link. Capacities were obtained primarily via the websites of the individual oil corporations operating the respective pipeline. A scheme of the pipeline network for the model is shown in Figure 4.

On average, transporting crude oil via pipeline costs \$5 per barrel [33]. Initial operational costs for each arc were then varied as a function of pipeline mileage. The mileage values were taken from individual corporation websites when available and estimated from digital maps otherwise. Some pipelines only provided capacity values at the terminals, and further investigation was required to ascertain the presence of major refineries between the terminals in order to properly account for changes in capacity. The pipelines were disaggregated to include separate arcs connecting refineries in different US states. The total capacity value of each pipeline was used as the initial capacity for the individual arcs thus created. In cases where multiple pipelines connected two nodes, capacities were aggregated into a single arc. As with the costs, pipeline capacities were modified during calibration to match baseline flows.

3.3.3 Waterways

Domestic transportation of crude oil through inland waterways (chiefly via the Mississippi and Ohio river systems) occurs via river-going barges, which typically have a capacity of 30 barrels. Coastal transport of crude oil, for instance, from Washington to California, is undertaken by tank barges or seagoing barges, which have a larger capacity of 90 barrels [34]. Imports and exports are undertaken by tankers, which have a greater capacity. Some refineries in Eastern Canada obtain shipments from the Gulf of Mexico, while some pipeline and rail movements bound for Canada originate from the northern US states.

Due to the Jones Act, vessels shipping domestic crude oil must be built and owned by US interests [34]. This severely restricts the domestic waterway shipping of crude oil and increases the costs by as much as three times that of using a foreign-owned vessel carrying foreign oil. Thus, in some situations, some refiners find it cheaper to import crude oil than to buy it from other regional suppliers who would have to ship it by barge to them [34].

Data on major inland routes were obtained from Ref. [34]. These routes connect states along the Mississippi and Ohio river systems. From the same source, we obtained initial shipping costs as well. We differentiated between tankers, river-going barges and seagoing barges—the key factor being the operational cost. Alaska, California and Washington were assigned incoming arcs from RW, as were nodes in the Gulf and on the East Coast (New Jersey, Texas, and others). Eastern Canada also has outgoing arcs to the eastern US refineries, while Mexico has outgoing arcs to the Gulf of Mexico states and RW. Mexico and RW are the only nodes in the model with a single mode of transport (ship) available to them.

3.4 Model calibration

Significant effort went into calibrating the model to produce results that matched observed quantities and prices for the base year of 2012. As production, transport and consumption figures for individual states (nodes) were not always readily available, regional data (by the PADD system⁶) were used as reference. In addition, it was useful to describe a region (Canada) including both the Eastern Canada and Western Canada nodes for the purpose of flow calibration. The classification of the producing and refining nodes by region is given in Table 1.

Table 1: Regions designated in the model

| Region | Supply and demand nodes |
|--------|----------------------------------------------------|
| CAN | Eastern Canada, Western Canada |
| MEX | Mexico |
| ONA | Rest of the World (RW) |
| PADD1 | Delaware, New Jersey, Pennsylvania |
| PADD2 | Kentucky, Minnesota, North Dakota, Ohio, Tennessee |
| PADD3 | Kansas, Louisiana, Mississippi, Oklahoma, Texas |
| PADD4 | Colorado, Montana, New Mexico, Wyoming |
| PADD5 | Alaska, California, Washington |

For the base year 2012, our model captured 82%, 85% and 91% of overall interregional rail, pipeline and waterway movements, respectively. The details are given in the Supplementary Information document ([Appendix](#)

⁵Some of the major systems and pipeline operators include: Colonial, Enbridge/Lakehead, Keystone, Marathon, Mid-Valley, Pony Express, Seaway, Spearhead, and TransCanada.

⁶A history and map of the PADD system are available at <https://www.eia.gov/todayinenergy/detail.cfm?id=4890>.

A). We have calibrated the model to EIA forecasts that are still based on an assumption of a crude oil export ban, and our scenarios therefore compare two futures: one with a ban (based on official projections), and the new status quo given our own results.

4 Results

Our results show that this model can be a useful tool for analyzing the the domestic crude oil market in the US, and in particular, providing solutions to transit problems in the network that present risks both to public-safety and to the environment. In the following subsections, we discuss the base case and four scenarios that investigate potential pathways for containing crude-by-rail flows while highlighting the capabilities of the model. The scenarios are as follows:

- (i) Restricting rail flows from the Bakken region/North Dakota
- (ii) Investing in pipeline capacity from the US Midwest
- (iii) Lifting the US crude oil export ban
- (iv) A concurrent implementation of the policies in (i), (ii) and (iii)

In each of the scenarios, all investment variables remained unchanged from the base case throughout the entire time horizon under investigation. Further, all the base year variables were fixed at base-case levels in the scenarios. These steps allowed for a consistent comparison.

4.1 The base case

Base case flows via rail and pipeline, according to the model, are depicted in Figure 5. Intrastate activity is not accounted for in either of these figures. Furthermore, the arcs are drawn to connect the centroid of each state and may therefore not fully reflect the geographical reality of the route represented.

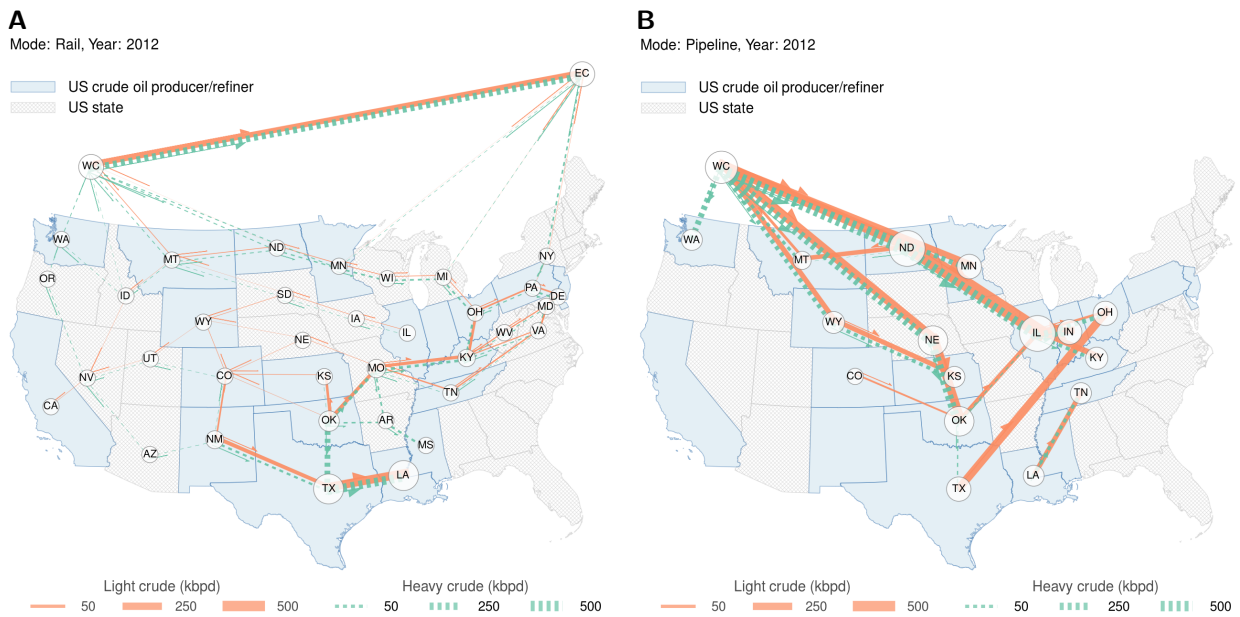


Figure 5: (A) Rail movements and (B) Pipeline movements of crude oil in the base year 2012. The size of the node labels indicate the larger of the quantities of crude leaving or entering the respective node.

Much of the rail movement in the US originated from the Northern Plains/Bakken region, which includes Montana, North Dakota. From the Midwest, trains were used to deliver crude oil to East Coast refineries. Rail also helped to lift both heavy and light crude to the Gulf of Mexico for refining or exporting. Along the West Coast, trains from Western Canada delivered crude oil to the Washington refineries and traversed California to deliver oil to neighboring states. Canada also depended on rail to move crude from west to east. While heavy oil production has surged in Western Canada, the absence of a cross-country crude oil pipeline system has paved the way for the rise in crude-by-rail shipments across the country. Eastern Canada also sends crude to New York refineries via rail.

The pipeline system in 2012 primarily conveyed oil from Western Canada to the US Midwest, and some ultimately to the Gulf Coast. Pipelines also moved oil through the Rockies (Montana, Wyoming, Colorado) toward Kansas and Oklahoma. Waterway movements are not shown. However, 3000 kbpd was imported into the Gulf of Mexico from RW in 2012, according to the model, while 800 kbpd and 900 kbpd were shipped into PADD1 (US East Coast) and PADD3 (US Gulf of Mexico) refineries, respectively. Mexico exported 240 kbpd to the rest of the world and 975 kbpd to PADD3. Canada sent 20 kbpd from its eastern shores to the rest

of the world, while 75 kbpd left for US East Coast refineries. Other smaller barge movements were captured, notably the 58 kbpd from PADD2 to PADD3, which represents traffic along the Mississippi river system.

4.2 Restricting crude-by-rail flows

In this scenario, we investigate the effects of directly capping rail flows from the Bakken region of North Dakota. The motivation behind this design was the growing concern over the rise of crude-by-rail across the heart of the country. In many instances, issues have been raised regarding the displacement of grain shipments by increasing crude oil loads. Also, the movement of crude-by-rail through California has been one of great concern, due to the fact that the rail lines pass through densely populated areas and close to water resources.⁷ Most importantly, the rising number of crude-by-rail accidents have spurred the authorities to take action.

In August 2015, the US Department of Transportation and Transport Canada jointly announced a “Final Rule” to govern the transit of crude oil via rail [35]. The stipulations provided by the Rule were adopted by the the Pipeline and Hazardous Materials Safety Administration and the Federal Railroad Administration, with input from the National Transportation Safety Board. The Rule aims to improve rail shipping standards by imposing speed reductions, tank car upgrades, enhanced braking requirements, routing regulations and stricter product classification. It has however been met with criticism from both industry and public administration representatives, who argue that the regulations are inadequate or too costly and disruptive to implement.⁸

A thorough implementation of this Rule will likely reduce crude-by-rail movements, especially from the Bakken region, and may encourage more pipeline deployment. To simulate the impact of these restrictions, we set rail arc capacities originating from the North Dakota area to half of the equilibrium rail transportation quantities in the base case. We choose North Dakota as it is a key driver of the growth in crude-by-rail shipments.

This scenario results in a disappearance of all westward US rail movements and those between the PADD5 nodes in 2015 (Figure 6A, B). While rail transportation in PADD5 is not completely eliminated in 2018, activity is limited only to California, Nevada and Washington, as compared to the base case in which all the nodes are involved in rail movements of crude oil (Figure 6C, D). Yet, in 2015, total US internodal rail flows in this scenario are only 5 kbpd less than in the base case (~1% decrease). One reason for this is the utilization of an alternate rail pathway for the crude oil from North Dakota to meet the demand in the Eastern US in the absence of sufficient pipeline capacity. By 2018, however, the impact of this restriction is seen in a 21% reduction in overall US rail movements from 9620 to 7554 kbpd. Meanwhile, pipeline throughput increases by nearly 1600 kbpd.

4.3 Pipeline investments in the US Midwest

The pressure on US oil transport infrastructure stemming from the Northern Plains has not only been due to increased oil production from the Bakken formation. Western Canada’s flourishing industry (driven by oil sands exploration in Alberta) has also contributed to rising demand for transfer to refineries and export terminals. As there is yet no pipeline connection from Alberta to Canada’s eastern shores and little capacity to Canada’s west coast, unrefined crude from the oil sands is transported to the gulf via pipeline through the Northern Plains, ultimately to the Gulf of Mexico. However, pipeline investments have not kept up with the rising production [21]. Where feasible, barge and rail flows have grown accordingly. The Keystone XL pipeline was proposed by TransCanada to boost capacity for throughput to the Gulf but this was rejected in 2015.⁹ A major player in the North American oil transit industry, TransCanada has also proposed the Energy East pipeline, with a maximum capacity of 1100 kbpd,¹⁰ to convey heavy crude from Alberta to Quebec. A decision on this project will be made by 2016. Like that of Keystone XL, the Energy East proposal has been met with mixed views amid concerns on possible impacts on communities and the environment vis-à-vis potential safety benefits over crude-by-rail transport.¹¹

While we closely follow ongoing pipeline developments in Canada, we shall initially focus on examining the situation in North Dakota, which has been the epicenter of outflows largely responsible for the growth in crude-by-rail shipments. North Dakota has approved the 12-inch 100 kbpd NST Express pipeline, scheduled to be in service by late 2016, to transport Bakken crude to Montana.¹² The massive 30-inch 570 kbpd Dakota Access Pipeline (DAP) is also on track to come online toward the end of 2016.¹³ The DAP will provide access to terminals in Illinois. Notably, TransCanada has also proposed the Upland Pipeline to carry up to 300 kbpd

⁷See G. Collins, “California crude trains: How much oil is actually coming in and where is it coming from?” North America Shale Blog, 2015 (<http://bit.ly/1HpU4E1>).

⁸See 2015 reports on the “oil train rules” by J. Mouawad at <http://nyti.ms/1bmdr6G> and <http://nyti.ms/1AVFv7V>.

⁹See New York Times report by C. Davenport, 2015, at <http://nyti.ms/1MN5hpl>.

¹⁰A description of the Energy East pipeline project is available from the NEB at <http://bit.ly/1kBCnr1>.

¹¹See CBC News article, “Hydro-Québec raises concerns about Energy East pipeline,” 2015 (<http://bit.ly/1T5qgEa>).

¹²See 2015 Bismark Tribune article by N. Smith at <http://bit.ly/1jrcbEq>

¹³See Bakken Magazine article for more information regarding the Dakota Access pipeline approval at <http://bit.ly/1S8z8Gt>.

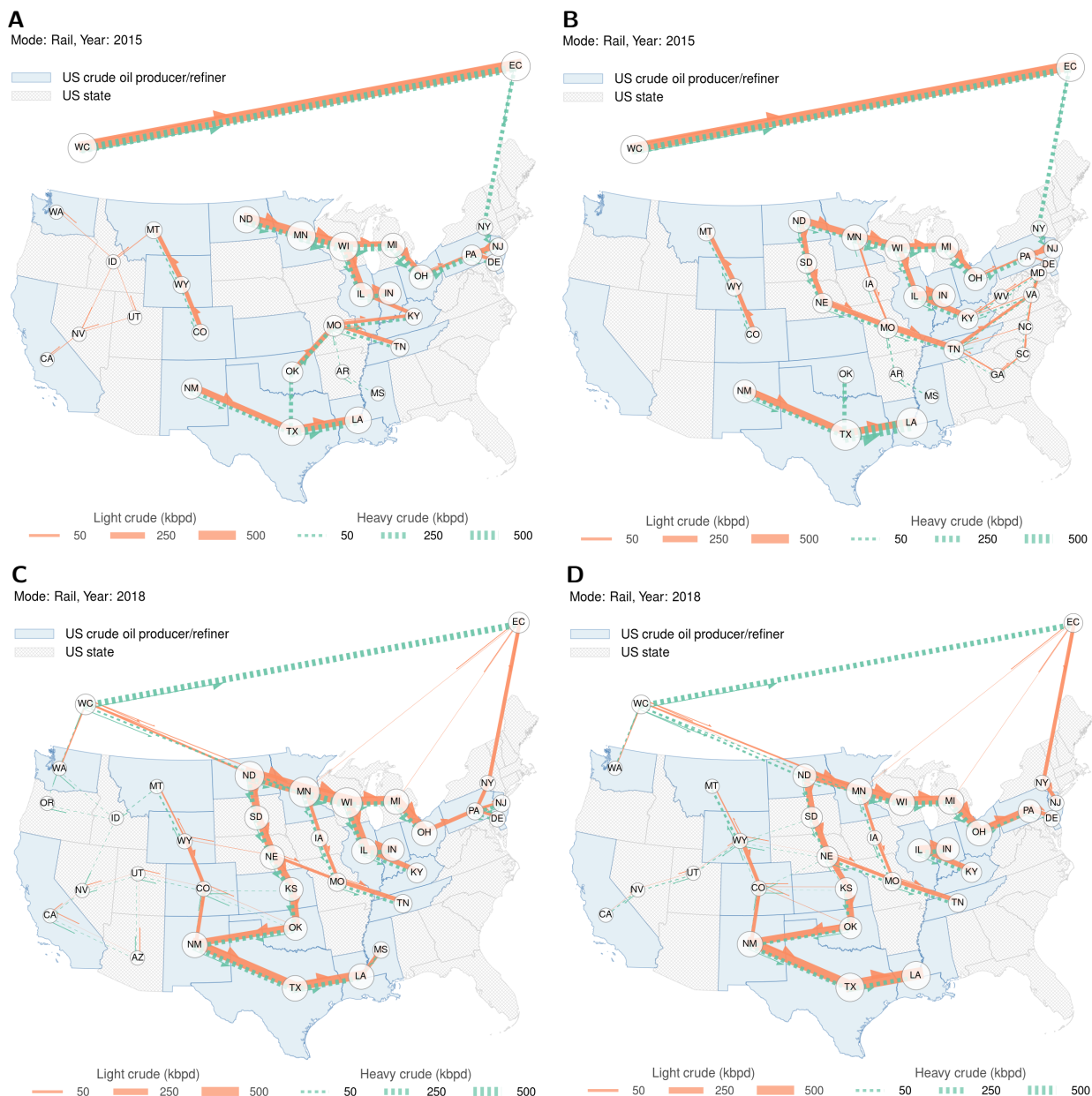


Figure 6: (A) Rail flows in the base case, 2015 (B) 2015 rail flows in the scenario “Capping Rail Flows From Bakken Region” in which surrounding rail capacities are set to half of the base case flows through those arcs. (C) Rail flows in the base case, 2018 (D) Rail flows of crude oil in 2018 under the scenario “Capping Rail Flows From Bakken Region.”

from North Dakota to Saskatchewan, but the Upland is not expected to join the pipeline network until 2020 if the project obtains the requisite approval.¹⁴

Given this outlook, we develop a scenario in which pipeline capacity in the US Midwest is expanded in both the eastern and western directions. Specifically, we add new pipeline connections from Michigan to New Jersey (eastward), and from Montana to Washington (westward). We also double pipeline capacity from North Dakota to Montana. The impact of these investments is seen in a transfer of 548 kbbpd of heavy-sour crude to the new Montana-Washington pipeline in 2015. In 2018, this pipeline carries 60 kbbpd of heavy-sour crude and 131 kbbpd of light-sweet crude. These in turn result in a reduction of crude-by-rail flows originating from the Bakken region (i.e. North Dakota). Yet, overall rail flows increase by 13% in 2015. These are due to the movements of about 200 kbbpd heavy-sour crude between Texas and Louisiana and also of 400 kbbpd heavy-sour crude between Washington and Oregon, with half of this volume going on to California. However, we see that there are fewer rail movements within PADD5 and between PADD4 and PADD5. In 2018, reductions in the total interregional rail flows are realized—a 9% decrease from 9620 kbbpd to 7123 kbbpd.

The newly added pipeline from Michigan to New Jersey, however, is left unused both in 2015 and 2018,

¹⁴See CBC News report: B. Nicholson, J. MacPherson, “TransCanada to seek US approval for \$600M Upland pipeline,” 2015, at <http://bit.ly/1VqYuGb>.

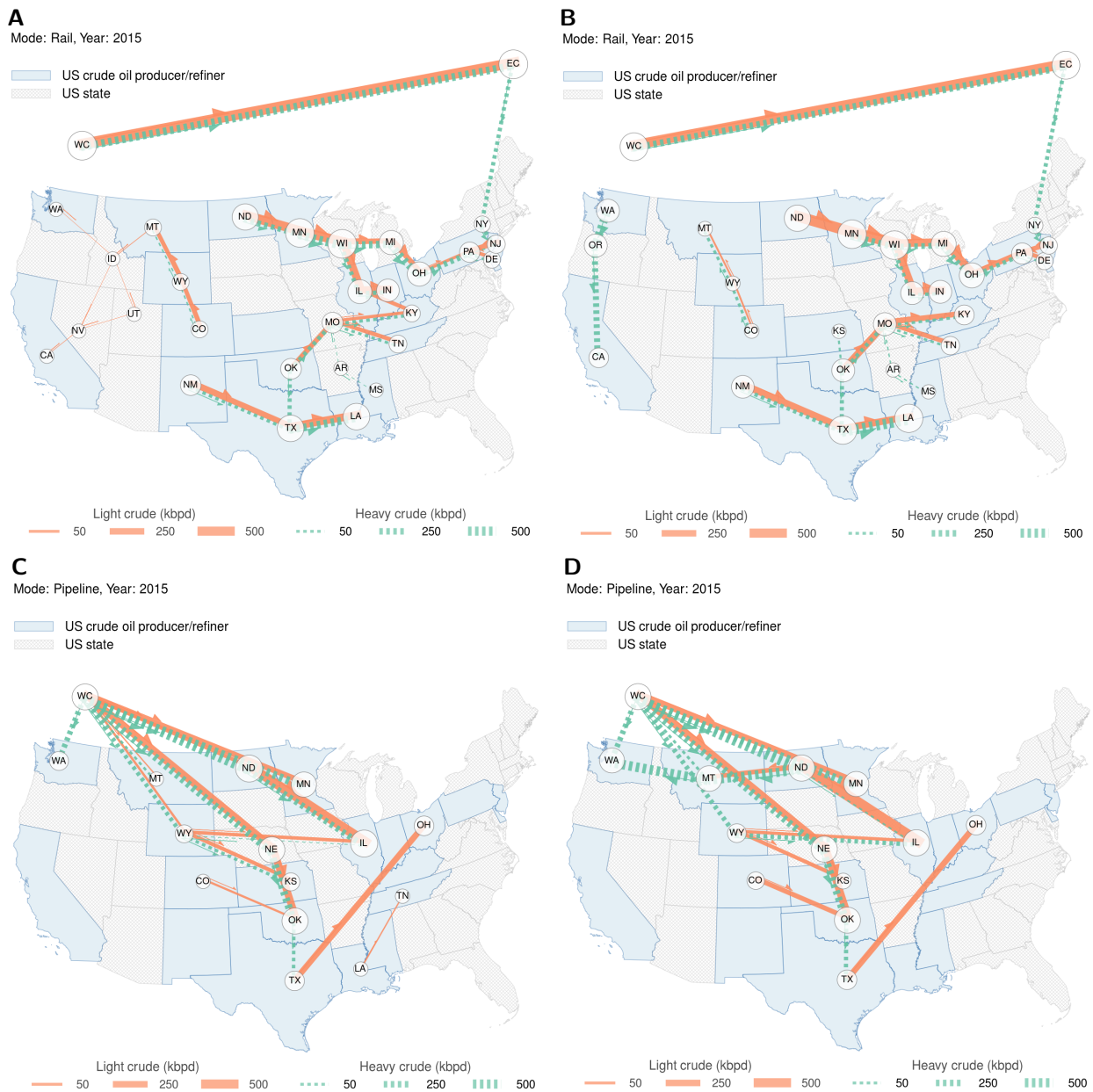


Figure 7: (A) Rail flows in the base case, 2015 (B) 2015 rail flows in the scenario “US Midwest Pipeline Investments” in which new pipelines are built to convey oil from North Dakota both to the east and west. (C) Pipeline flows in the base case, 2015 (D) Pipeline flows of crude oil in 2015 under the scenario “US Midwest Pipeline Investments.”

indicating that it may not be a viable investment due to the relative cost of transfer. The rail and pipeline flows in 2015 compared to the base case are shown in Figure 7.

4.4 Lifting the US crude oil export ban

The US effectively banned domestic crude oil exports when President Gerald Ford signed the Energy Policy and Conservation Act into law in 1975 [36, 37]. At the time, the country was experiencing a decline in oil production. Moreover, it had recently endured an economic crisis when OPEC imposed a retaliatory oil export embargo on the US [37]. National sentiment was therefore understandably in favor of shoring up reserves and increasing domestic supply.¹⁵ Canada was exempt from this ban. Thus, any unrefined oil from the US invariably finds its way to Canada. Alaska had also been exempt from the ban since 1995, but its export volumes began to dwindle in the late 1990s.¹⁶ Only in 2014, after a decade-long hiatus,¹⁶ did it send its first export shipment—784 kilobarrels to South Korea¹⁷ (about 2 kbpd).

¹⁵J. Bordoff presented data suggesting that strong opinions against oil exports still persisted among the general public in 2014 (<https://www.eia.gov/conference/2014/pdf/presentations/bordoff.pdf>).

¹⁶For a brief context on Alaska oil shipments, refer to J. A. Dlouhy’s post at <http://bit.ly/1WsVhou>

¹⁷See Los Angeles Times report by M. Muskal, 2014, at <http://fw.to/GFJiL7J>

Considering the recent boom in US domestic production, the ban had been increasingly perceived to be more of a hindrance than a boon [38]. A large portion of new crude oil supplies is of the light-sweet variety, for which refining capacity is not readily available at the source. Thus, producers have had to incur expensive transportation costs to deliver crude oil to refineries. Experts argued that an end to this export restriction could only benefit the economy [37, 39] and increase the competitiveness of the US oil industry. More crucially, authorizing crude oil exports could also relieve demand on strained transit infrastructure, especially rail. Notably, the US Congress supported a plan to lift the ban in December 2015.¹⁸ The spending bill including a provision authorizing exports of domestically produced oil was finally passed and signed into law before the end of the year, thus ending the 40-year prohibition.¹⁹

We investigate the impact of lifting this decades-long ban by implementing a scenario in which shipping capacity is added from US coasts to the rest of the world. These shipping arcs are incident from California, Washington (West Coast), Louisiana, Texas (Gulf of Mexico) and New Jersey (East Coast) in the model scenario.

Under this scenario, Texas (which also represents the Gulf of Mexico in this model) exports 405 kbpd in 2015 and 324 kbpd in 2018. (Alaska also exports 5 kbpd in both years, but it was exempt from the ban and its exports are therefore present in the base case as well.) More significant, however, is the reduction in imports into these regions. The net imports via waterways can thus be seen as an indicator of the new export volumes (Table 2). These movements, however, do not reduce the pressure on the rail network as intra-US flows increase

Table 2: Net imports of crude oil into the US via ship (tankers) in the base case [BC] compared to those in the “US crude oil export ban lifted” scenario [EBL], for the years 2015 and 2018.

| Incoming Region | 2015 | | | 2018 | | |
|-----------------|-----------|------------|--------|-----------|------------|--------|
| | BC (kbpd) | EBL (kbpd) | % drop | BC (kbpd) | EBL (kbpd) | % drop |
| PADD1 | 630 | 630 | 0 | 860 | 675 | 22 |
| PADD3 | 4050 | 2395 | 41 | 4350 | 2585 | 41 |
| PADD5 | 1245 | 1160 | 7 | 1364 | 516 | 62 |

by 12% from 7122 kbpd in 2015 (base case) to 7945 kbpd. In 2018, a similar trend is observed with a 22% rise from 9620 kbpd to 11750 kbpd in US crude oil movements. The quantity transported via pipeline also increases accordingly while the volume of waterway transportation decreases. This result indicates that the opening of the global market to US would lead to increased land transport in order to satisfy demand.

4.5 US exports, Midwest pipeline investments and Bakken rail caps

This scenario is a simultaneous implementation of the three policies already considered: capping rail flows from the Bakken region, building two pipelines—one from North Dakota and the other from Michigan, and lifting the US crude oil export ban.

In 2015, the new Michigan-New Jersey pipeline is utilized to supply 164 kbpd of heavy-sour crude to the East Coast, which replaces oil tanker movements from Eastern Canada. Meanwhile, the other new pipeline from Montana to Washington transports 367 kbpd of the same quality of crude. Accordingly, net imports in PADD5 fall to 805 kbpd, a 35% decrease compared to the base case. With the Bakken rail cap in effect, intra-US rail movements drop by 2% to 6995 kbpd, as intra-US pipeline movements increase by 37% to 5279 kbpd.

In 2018, the capacity of the newly added Montana-Washington pipeline is fully utilized. Exports to RW from PADD5 are registered at a value of 336 kbpd. About two-thirds of this volume is light-sweet oil from the Bakken region. Meanwhile, actual imports fall to 356 kbpd, reducing net crude imports at PADD5 to 20 kbpd.

Net imports at PADD3 in both years are slightly higher than in the “US Crude Oil Export Ban Lifted” scenario but still considerably lower than in the base case (less 31% and 33%, respectively). A similar situation can be seen for PADD1 in 2018. In terms of intra-US rail flows, however, the key result is a 26% reduction relative to the base case. With no restrictions on exports, the new pipelines and the rail caps result in more oil being transported to PADD5, making the region more important as an exporter of crude. Thus, less crude oil moves to PADD3 and thereby reducing the crude-by-rail impact in the US.

5 Discussion

Crude-by-rail flows within the US are reduced under the “Capping Bakken Rail Flows” and “US Midwest Pipeline Investments” scenarios, but these improvements are not realized until 2018, with decreases of 21% and

¹⁸Details on this plan were reported by B. House et al., “Pelosi, White House support plan allowing US crude oil exports,” Bloomberg Politics, 2015. <http://bloom.bg/1P69q61>.

¹⁹See Wall Street Journal report: K. Peterson, “Congress passes \$1.15 trillion spending bill,” 2015 (<http://on.wsj.com/10cL9hq>)

9% respectively. In the counterfactual scenario analysis for the year 2015, restricting the rail capacities from the Bakken Region results in only a 1% reduction. We note that while the pipeline investments result in a 13% increase in rail flows in 2015, the impact is only limited to two pairs of neighboring states: Texas-Louisiana and Washington-Oregon. Thus, the ability to analyze flows at the US state level will be important for more accurate determinations of the environmental effects of crude oil transportation.

In the “US Oil Export Ban Lifted” scenario, rail flows increase in both years, indicating that simply lifting the crude oil export ban in the US will not solve the crude-by-rail problem in the medium term. However, when this is done in conjunction with pipeline investments and Bakken rail caps, maximum reductions in overall US rail flows are realized, both in 2015 and 2018. Table 3 shows the relative rail flow changes across the

Table 3: Changes in crude-by-rail scenario flows relative to the base case [BC] among the US nodes (states) in 2015 and 2018.

| Scenario | 2015 | | 2018 | |
|-----------------------------------------------|-------------|----------|-------------|----------|
| | Flow (kbpd) | % change | Flow (kbpd) | % change |
| Base Case | 7123 | 0 | 9620 | 0 |
| Capping Bakken Rail Flows | 7128 | -1 | 7554 | -21 |
| US Midwest Pipeline Investments | 8077 | +13 | 8771 | -9 |
| US Oil Export Ban Lifted | 7945 | +12 | 11750 | +22 |
| US Exports+Midwest Pipelines+Bakken Rail Caps | 6992 | -2 | 6147 | -26 |

scenarios. The modal shares in each scenario are compared in Figure 8. In all the scenarios considered, there is no significant difference in consumer welfare with respect to the base case. This indicates that no one scenario has a particular advantage for the benefit of the refining sector.

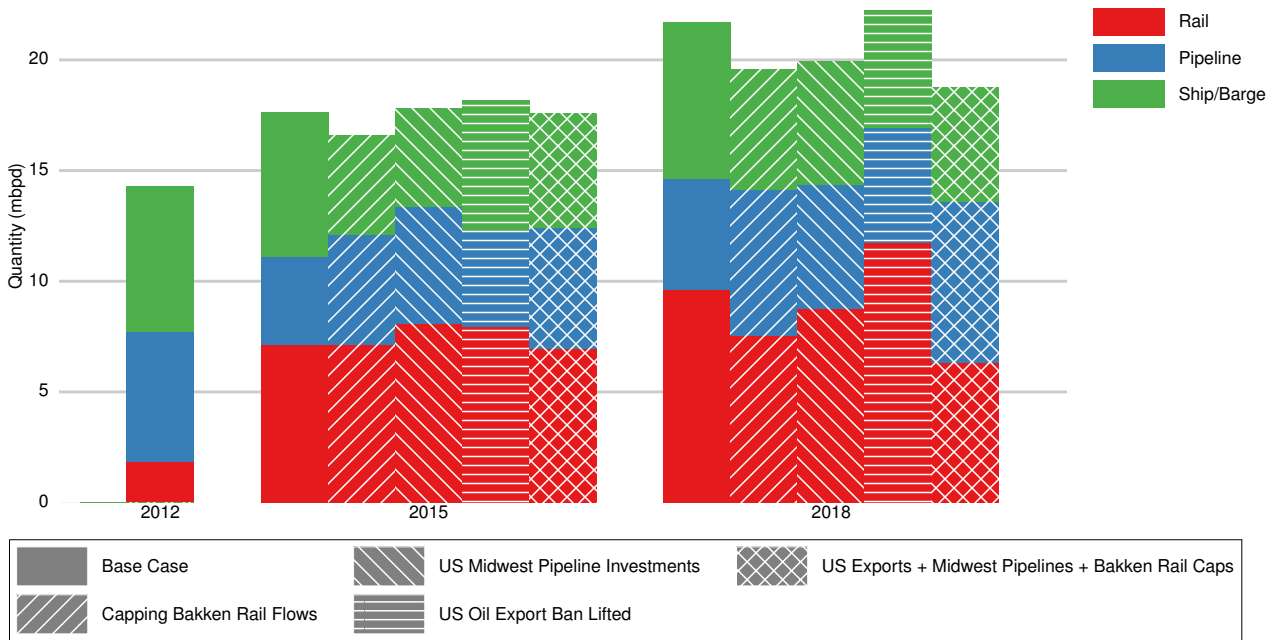


Figure 8: Multimodal interstate (US) crude oil flows by scenario

Generally, these results show that in the near-to-medium term, restricting loading capacities from the Bakken region is a consistently effective means of containing crude-by-rail flows. Investing in pipeline capacity from the same region will also eventually contribute to reducing rail movements. A joint implementation of these strategies, however, provides the best mitigation of crude-by-rail.

6 Outlook

We have presented a medium-term model of the North American crude oil market with US state level granularity, which is a first in the literature to capture distinct crude oil qualities and the different modes of transportation across the continent. A key aspect of this effort was the investigation of the reduction of crude by rail with a focus on flows originating from the Bakken region in North Dakota. Two scenarios were implemented

in this regard. We also considered the lifting of the US crude oil export ban. Finally, we investigated a fourth scenario in which the policies of the first three scenarios are jointly implemented. Our results show that capping the rail flows from North Dakota or investing in pipeline capacity from the same area can help reduce the rail throughput in the US. While only lifting the export ban results in increased rail flows, combining the export ban lifting with pipeline investments and rail caps provides the lowest crude-by-rail flows in the medium term up to 2018. All scenarios were similarly beneficial to the refining sector. These outcomes suggest that integrated approaches are more likely to be successful in tackling the crude-by-rail problem.

We have not fully treated the issue of emissions and quantifying the environmental impact of crude oil transportation. This is certainly a growing concern that deserves a considerable amount of thought. Our model remains relevant in addressing this issue. In our subsequent effort, we can then consider the environmental factors in each of the scenarios we design. An important development in the last year was the creation of the Oil Climate Index [40]. This would be valuable in future work to quantify the environmental impact of crude oil production in North America, particularly with regard to climate.

With regard to crude oil types, we differentiated between the heavy and light qualities. On the production side, the heavy-to-light ratios were obtained from various industry reports and estimated otherwise. US refining capacities for both qualities were deemed from average API gravity values of refined crude in each state as reported by the EIA. A report recently released by the American Fuel & Petroleum Manufacturers provides details on US regional crude oil refining capacities and output by quality [41]. Future work could incorporate these results along with the data also collected by Langer et al. [12] in their study.

At this stage of development, the model does not account for storage. Along with Cushing, Oklahoma, which serves as a major hub of crude oil movements originating both in Canada and the US, there are other major holding facilities, notably the Louisiana Offshore Oil Port system (LOOP), that influence market dynamics.²⁰ In recent years, storage has become a major concern in the industry as capacity is being stretched [4, 42]. Obtaining data on storage capacities and modeling the hub activity at Cushing is an improvement we hope to make in the subsequent iteration of this modeling effort. This will also enable us to better capture the complex movements between the US Midwest and the Gulf of Mexico.

One other promising avenue for future work is the combination of this model with others currently being developed for natural gas [43] and biofuels [44, 45] in North America. The strategic importance of the US in the global gas market is steadily rising [1, 46], even as it vigorously pursues a robust biofuel policy. The intersecting implications of these trends to climate, security, economy and industry are wide-ranging [2, 47, 48, 49]. We would therefore want to consider the effects of fuel substitution to obtain a better picture of the oil, gas and biofuel markets, while developing more robust scenarios to aid decision-making in addressing challenges, especially in North America.

Critical advances have been made in US energy policy, and the viability of renewables, such as biofuels, is rising. Yet, crude oil will remain a major component of the US energy landscape for the next several decades [50], and integrated approaches will be key to finding optimal strategies for crude oil in the multifuel energy system [51]. In Canada, crude oil is still considered a mainstay of the nation's economy, as investments in production capacity and transportation continue to grow [52, 6]. With proper reform, Mexico's oil industry can overcome current inefficiencies to transform its energy sector and economy [24, 23]. The recently approved crude oil swap between the US and Mexico is also expected to be mutually beneficial to US exporters and Mexico refiners [53]. Given these trends, there will exist a need in the near-to-medium term to find the best intersections for policy and market decisions to minimize the environmental impact of crude oil production and transportation on the continent.

Acknowledgements

This work was partially supported by the Gordon Croft Fellowship awarded by the Energy, Environment, Sustainability and Health Institute (E²SHI) at The Johns Hopkins University. For their valuable comments and suggestions, we thank: Lissy Langer (TU Berlin), Gary Lin and Dr. Felipe Feijoo (Johns Hopkins Systems Institute). We are also grateful to David Livingston and Eugene Tan (Carnegie Endowment for International Peace) for their time and insightful conversations.

²⁰D. Murtaugh reports on current oil movement trends at LOOP in the Bloomberg article at <http://bloom.bg/1zUyB7q>.

Glossary

| | |
|-------|---------------------------------------------------|
| API | American Petroleum Institute |
| CAPP | Canadian Association of Petroleum Producers |
| EIA | Energy Information Administration (US) |
| kbpd | thousand barrels per day |
| MCP | Mixed Complementarity Problem |
| mbpd | million barrels per day |
| NEB | National Energy Board (Canada) |
| OPEC | Organization of the Petroleum Exporting Countries |
| PADD | Petroleum Administration Defense District |
| Pemex | Petróleos Mexicanos |
| RW | Rest of the World (excluding North America) |
| US | United States |

Appendix A Supplementary information and data

A complete formulation of the model and flow calibration details are provided in the Supplementary Information document. The data and supporting methods are publicly available at ce.jhu.edu/sauleh/nacom.

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