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Multimodal transportation flows in energy networks with an application to crude oil markets

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Abstract Network models of energy markets have been beneficial for analyses and decision-making to tackle challenges related to the production, distribution and consumption of energy in its various forms. Despite the growing awareness of environmental and safety impacts of fuel transfer, such as emissions, spills and other harmful effects, existing energy models for various types of networks are yet to fully capture modal distinctions which are relevant to providing pathways to limiting these impacts. To address this deficit in detailed multimodal analyses, we have built on recent work to develop a partial-equilibrium model that incorporates the representation of multimodal fuel transfer within energy networks. In a novel application to the North American crude oil market, we also demonstrate that our model is a useful tool for exploring avenues for reducing the risks of light and heavy

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crude oil transportation across this region. The results we obtain indicate that a combined strategy of rail loading restrictions, pipeline deployments and a discontinuation of the oil export ban is most effective in reducing the transportation of crude oil by rail and thereby mitigating the associated risks.

1 Introduction

Multimodal flow analyses are critical to characterizing and solving problems within today's energy networks. The movement of fuels between nodes and across various levels within these networks involves multiple decisions under uncertainty and constraints of capacity, regulation and environmental impact limitation (Melese et al, 2016). As urgent steps are being taken to tackle climate change and related effects, greater efforts must be made to capture salient properties of various modes of energy transfer in order to provide reliable frameworks for best policy implementations (Heijnen et al, 2014). This is especially important for existing energy networks that negatively impact the environment, such as fossil fuel markets, as they must be properly managed while they are yet relevant.

Networks are primarily defined by their topology, which constrains internodal movements or connections. Within certain networks, arcs may be differentiated by mode of travel or conveyance. Network models have been successfully used to describe complex systems in order to solve a variety of problems, including those of allocation, equilibrium, flow optimization, prediction, scheduling, among others. With appropriate calibration, these types of models can also allow for intervention experiments and scenario analyses. For energy applications in particular, we are often interested in optimizing player objectives, finding a market equilibrium and making decisions while limiting harmful effects, such as greenhouse gas emissions. Implementing scenario analyses provides multiple layers for subsequent policy intersections.

Various modeling approaches have been employed for energy markets including multiobjective optimization and linear programming, but complementarity modeling has grown in importance given its ability to capture complex network interactions (Ruiz et al, 2014; Gabriel et al, 2013a). Mixed complementarity problems (MCPs) generalize equilibria and nonlinear programs, and they can be solved by a variety of Newton-based methods (Ferris and Pang, 1997). In a competitive marketplace, each player's optimization problem can be expressed as a set of Karush-Kuhn-Tucker (KKT) equations (Kuhn and Tucker, 1951). 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 (Nash, 1951). The scope of energy applications in complementarity modeling is highlighted through the following examples: Abrell and Weigt (2012) developed an MCP model with a focus on investigating interactions between energy networks. Similarly, Huppmann and Egging (2014) formulated a complementarity model that accommodates multiple fuels and markets and features fuel substitution, which they applied on a global scale. Showing that discretely-constrained Nash games could be implemented as MCPs, Gabriel et al (2013b) modeled energy

networks with new approaches to finding solutions. Metzler et al (2003) also used an MCP to model the Nash-Cournot equilibrium between market players, exhibiting its capability to characterize arbitrage in a power network. In an application to gas markets, Abada et al (2013) employed a variational inequality formulation, which is a special case of an MCP. Christensen and Siddiqui (2015) captured the complex interactions in a biofuel market also using a complementarity model.

We want to note that there exist a wide variety of modeling techniques for energy systems that are not optimization- and equilibrium-based (Lin and Magnago, 2017; Jebaraj and Iniyan, 2006; Suganthi and Samuel, 2012). These techniques provide detail in different parts of the energy system, such as extraction, physical processes, and generation. As such, these models can be useful in answering specific questions pertaining to these processes. Given that our goal here is to consider a "what-if" policy analysis under different market scenarios, we chose to use equilibrium problems expressed as complementarity problems. This allows us to explicitly represent infrastructure under different market interactions.

In this paper, we present a dynamic multimodal partial-equilibrium model built as an MCP and applicable to multifuel energy networks. Notably, the model features modal differentiation in order to accurately account for the distinct effects of each mode of conveyance in the energy network of interest. We consider this a major contribution as prior energy market models did not distinguish between modes of transportation for internodal transfer. Thus, they were not able to account for variations in cost and technology based on mode choice. Given the increasing concerns relating to environmental and climate impacts, modal disaggregation provides for detailed analyses of emissions contributions and safety risks of each flow variable. Consequently, various intersections can be examined and scenarios explored either to minimize or mitigate these risks and hazards. As an illustration of its capabilities, we apply this model to the North American crude oil market with transportation considered via railway, pipeline and waterway [river and sea] modes, as well as distinguishing between light and heavy crude oil qualities. We then perform scenario analyses to explore avenues for reducing the public-safety and environmental impact of crude-by-rail transport. This application and level of node disaggregation at the US state level in the North American market is also a first in the academic literature, and we also note that no model for North American crude with transfer mode specificity exists. Our model can be potentially coupled with climate assessment models for further impact-based decision and policy analyses. Furthermore, its multimodal features can be incorporated into existing energy-optimization-complementarity models.

The remainder of the paper is organized as follows. Section 2 gives a detailed description of the model, its mathematical formulation and implementation. In Section 3, we motivate and discuss the application of this model to the North American oil market. The results of this modeling effort and analyses are explained in Section 4. We discuss their impact and implications in Section 5, while Section 6 provides avenues for future work. Section 7 summarizes and concludes the paper.

2 Model description

As mentioned in the previous section, this is a partial-equilibrium model that captures the non-cooperative game between market players, which comprise the

producers (supply side), transporters and consumers (demand sector). The model is built with an MCP framework which accounts for quantities, prices and constraints across all sectors. The KKT conditions are formulated from the optimization problems of the suppliers, the arc operators and the demand sector, each with their own sets of constraints. These optimization problems are detailed in the following three subsections (Subsection 2.2, Subsection 2.3, Subsection 2.4). The relevant set descriptions are given in Table 1.

Table 1 Selected sets and mappings

$y \in Y$	Years
$s \in S$	Suppliers
$n, k \in N$	Nodes
$m \in M$	Modes of fuel transfer
$a \in A$	Arcs
$a \in A^+_{nem} \subseteq A$	Arcs ending at node n transporting fuel e via mode m
$a \in A^-_{nem} \subseteq A$	Arcs starting at node n transporting fuel e via mode m
$d \in D$	Demand sector
$e, f \in E$	Fuel type

A complete enumeration of the parameters and variables used in this model are given in Table 2. This model follows the traditional formulation of a number of existing models (Huppmann and Egging, 2014; Feijoo et al, 2016; Abrell and Weigt, 2012; Egging et al, 2010). However, ours in an improvement in that we have contributed toward the implementation of multimodal flows.

Table 2 Model parameters and variables

Production	avl^P_{ysne}	availability factor, production capacity
	gol^P_{ysne}	logarithmic term, production cost function
	hor^P_{ysne}	production horizon (reserves)
	lin^P_{ysne}	linear term, production cost function
	loss^P_{sne}	loss rate, production, node n, fuel e
	qud^P_{ysne}	quadratic term, production cost function
	α^P_{ysne}	production capacity constraint dual
	γ^P_{ysne}	production horizon constraint dual
	q^P_{ysne}	quantity produced
	z^P_{ysne}	production capacity expansion
Transportation (Arcs)	cap^A_{yam}	capacity, arc a in year y
	dep^A_{yam}	depreciation of arc capacity expansion
	exp^A_{yam}	capacity expansion limit, arc a year y
	inv^A_{yam}	unit investment costs, arc capacity expansion
	loss^A_{am}	loss rate, transit via arc a
	trf^A_{yam}	tariff, arc a in year y
	f^A_{yam}	operator arc flow
	p^A_{yaem}	arc capacity market clearing price
	q^A_{ysaem}	quantity transported, arc a
	τ^A_{yam}	arc capacity constraint dual
	z^A_{yam}	arc capacity expansion dual
	ζ^A_{yam}	arc capacity expansion limit dual
Demand	eff^D_{yne}	efficiency, demand satisfaction, fuel e
	eucc^D_{yne}	constant term, end use cost function
	eucl^D_{yne}	linear term, end use cost function
	int^D_{yn}	intercept, inverse demand function, node n
	slp^D_{yn}	slope, inverse demand function, node n
	p^D_{yne}	final demand price of fuel e
	q^D_{ysne}	quantity sold to refinery sector
Other	ϕ_{yne}	mass balance constraint dual

2.1 Model implementation

The program is written in GAMS, a high-level modeling language.[1] In the initialization stage of the model, variable declarations and parameter assignments are made based on the data supplied. An algorithm is then run 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 starting points for the supply prices are assigned from the solution obtained. An automated iterative calibration algorithm then matches consumption at all nodes to reference levels, manipulating the end-use cost parameters in the process (Huppmann and Egging, 2014). We manually calibrate the model parameters such that the results coincide with reference production and regional transportation quantities for the base year. This process is nontrivial, as it requires the adjustment of costs, both for production and transportation. The program utilizes the PATH solver (Ferris and Munson, 2000) to obtain an equilibrium to the non-cooperative game between market participants.

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[1] General Algebraic Modeling Systems (GAMS), release 23.9.5; GAMS Development Corporation, https://www.gams.com/.

2.2 Supply side profit maximization

The supplier maximizes profit from the quantity of product q^D sold at market price p^D, taking into account costs of production, transportation, emissions and future investment in production capacity (1). The term $\text{cost}^P_{ysne}(\cdot)$ represents the production cost function, while p^A and p^G are the unit equilibrium prices of fuel transported via the arcs and production-based emissions, respectively. The variables q^A and q^P are the quantities produced and transported, respectively, while inv^P and z^P are the unit investment costs and the size of the investment (expansion of capacity), respectively.

$$\max_{\substack{q^P,q^A \\ q^D,z^P}} \sum_{\substack{y \in Y \\ n \in N \\ e \in E}} \text{df}_y \left(p^D_{yne}q^D_{ysne} - \text{cost}^P_{yse}(\cdot) - \sum_{a \in A^+_{nem}} p^A_{yaem}q^A_{ysaem} - \text{inv}^P_{ysne}z^P_{ysne} \right) \tag{1}$$

The production cost function (2) is logarithmic (Golombek et al, 1995; Huppmann, 2012) in order to adequately represent the behavior of the marginal cost (3), which becomes prohibitive as production approaches capacity, and the decreasing effect the investment has on future costs of production (4).

$$\text{cost}^P_{ysne}(\cdot) = \left(\text{lin}^P_{ysne} + \text{gol}^P_{ysne} \right) q^P_{ysne} + \text{qud}^P_{ysne}(q^P_{ysne})^2$$
$$+ \text{gol}^P_{ysne} \left(\widehat{\text{cap}}^P_{ysne} - q^P_{ysne} \right) \ln \left(1 - \frac{q^P_{ysne}}{\widehat{\text{cap}}^P_{ysne}} \right) \tag{2}$$

$$\frac{\partial \text{cost}^P_{ysne}(\cdot)}{\partial q^P_{ysne}} = \text{lin}^P_{ysne} + 2\text{qud}^P_{ysne}q^P_{ysne} - \text{gol}^P_{ysne} \ln \left(1 - \frac{q^P_{ysne}}{\widehat{\text{cap}}^P_{ysne}} \right) \tag{3}$$

$$\frac{\partial \text{cost}^P_{ysne}(\cdot)}{\partial z^P_{\hat{y}sne}} = \text{gol}^P_{ysne}\text{avl}^P_{ysne}\text{dep}^P_{\hat{y}ysne} \left[\ln \left(1 - \frac{q^P_{ysne}}{\widehat{\text{cap}}^P_{ysne}} \right) + \frac{q^P_{ysne}}{\widehat{\text{cap}}^P_{ysne}} \right], \hat{y} < y \tag{4}$$

$$\widehat{\text{cap}}^P_{ysne} = \text{avl}^P_{ysne} \left(\text{cap}^P_{ysne} + \sum_{y' < y} \text{dep}^P_{y'ysne}z^P_{y'sne} \right) \tag{5}$$

The supplier profit maximization problem (1) is subject to the following constraints:

$$q^P_{ysne} \leq \text{avl}^P_{ysne} \left(\text{cap}^P_{ysne} + \sum_{y' < y} \text{dep}^P_{y'ysne}z^P_{y'sne} \right) \qquad (\alpha^P_{ysne}) \tag{6}$$

$$q^D_{ysne} = (1 - \text{loss}^P_{sne})q^P_{ysne} + \sum_{a \in A^+_{nem}} (1 - \text{loss}^A_a)q^A_{ysaem} - \sum_{a \in A^-_{nem}} q^A_{ysaem} \qquad (\phi_{ysne}) \tag{7}$$

$$z^P_{ysne} \leq \text{exp}^P_{ysne} \qquad (\zeta^P_{ysne}) \tag{8}$$

$$\sum_{y \in Y} q^P_{ysne} \leq \text{hor}^P_{sne} \qquad (\gamma^P_{sne}) \tag{9}$$

The inequalities (6) and (9) are both production capacity constraints. The first constraint bounds production to the availability of combined capacity (initial and expanded). The second simply ensures that total production over all time periods considered does not exceed proven reserves. Constraint (7) ensures nodal mass balance, while also accounting for fuel transport losses. An upper bound for invested capacity expansion is ensured by (8).

2.3 Fuel transport profit maximization

The independent arc operators seek to maximize profit by transporting fuel via their respective arcs, which are differentiated by mode and fuel type. In computing the profit for each arc, the price p^A, less the cost of operating the arc trf^A, is multiplied by the flow f^A, while taking investment costs into account (10). Each of these terms are considered on a mode-by-mode basis, as differences arise depending on the mode of conveyance. This is also the case for other arc parameters, such as capacity cap^A. In a crude oil network, for instance, injection and removal capacities for rail cars are often two orders of magnitude smaller than those of pipelines. Depending on the distances involved, investment costs, operating costs and capacities between, say, truck and ship will obviously be vastly different. The initial values of the mode-dependent parameters can be obtained or estimated from available data. Emissions and related costs are not considered.

$$\max_{f^A, z^A} \sum_{y \in Y} \text{df}_y \left[\left(p^A_{yam} - \text{trf}^A_{yam} \right) f^A_{yam} - \text{inv}^A_{yam} z^A_{yam} \right] \tag{10}$$

$$\text{s.t.}$$

$$f^A_{yam} \leq \text{cap}^A_{yam} + \sum_{y' < y} \text{dep}^A_{y'yam} z^A_{yam} \quad (\tau^A_{yam}) \tag{11}$$

$$z^A_{yam} \leq \exp^A_{yam} \quad (\zeta^A_{yam}) \tag{12}$$

$$\sum_{s \in S} q^A_{ysaem} = f^A_{yaem} \quad (p^A_{yaem}) \tag{13}$$

The constraints provide bounds for flow (11) and capacity expansion (12) in each arc. The decision to invest in expanding arc capacity is undertaken if the cost inv^A of doing so is less than the dual τ^A of the flow constraint. The arc usage price p^A is determined by the market clearing constraint equation (13). Transportation networks are complex and always expanding (Xie and Levinson, 2009). However, our model can be easily extended to include other modes and capture their characteristics.

2.4 Demand sector welfare maximization

On the demand side, the goal is utility maximization from energy use in the demand sector, which in our case is represented solely by the refining industry. This produces a quadratic problem (14), where Q^D represents all variables constituting the final demand.

$$\max_{Q^D} \quad \sum_{\substack{y \in Y \\ n \in N \\ e \in E}} \left[\text{int}_{yn}^D - \tfrac{1}{2}\text{slp}_{yn}^D \left(\sum_{f \in E} \text{eff}_{ynf}^D Q_{ynf}^D \right) \right] \text{eff}_{yne}^D Q_{yne}^D - p_{yne}^D Q_{yne}^D \tag{14}$$
$$- \text{eucc}_{yne}^D Q_{yne}^D - \tfrac{1}{2}\text{eucl}_{yne}^D (Q_{yne}^D)^2$$

For tractability, this problem is linearized via first-order conditions. The resulting inverse demand function is realized as the market-clearing price p^D for each fuel, and the final demand Q^D as the refinery demand from all suppliers $\sum_S q^D$.

$$p_{yne}^D = \text{eff}_{yne}^D \left[\text{int}_{yn}^D - \text{slp}_{yn}^D \left(\sum_{s \in S, f \in E} \text{eff}_{ynf}^D q_{ysf}^D \right) \right] \tag{15}$$
$$- \text{eucc}_{yne}^D - \text{eucl}_{yne}^D \left(\sum_{s \in S} q_{yse}^D \right)$$

The market-clearing price p^D consists of the effective composite price of the energy supply (the first term in (15)), where slp^D and int^D are the slope and intercept, respectively, of the energy supply demand function. End-use costs for each fuel are also taken into account by a linear function parameterized by eucl^D (linear term) and eucc^D (constant term)[2].

2.5 Model properties

The current model structure is that of an equilibrium problem, with the assumption on bounded rationality that can be cast as a Nash-Cournot problem. However, in many applications, the players can choose to be strategic with respect to their behavior, such as exercising market power (Huppmann et al, 2015). While some aspect of strategic behavior can be included within this problem structure (Iwata, 1974; Garcia et al, 2014; Day et al, 2002), a more general formulation leads to multi-leader, multi-follower games (Yao et al, 2008, 2007; DeMiguel and Xu, 2009; Kulkarni and Shanbhag, 2014), modeled as problems with equilibrium constraints (Siddiqui and Christensen, 2016). Proving existence of equilibria in these settings is not straightforward, and the computational burden for solving these problems is much higher. While our current problem structure cannot yield the full representation of player behavior, it still yields insights in the basic equilibrium setting and is computationally tractable. We hope that future work extends our current model to more strategic behavior settings with new computational tools to solve these problems.

Note that the constraints for each player's optimization problem form a nonempty, compact, convex set. Further, the objective functions as stated for the minimization problems are quasi-convex, which means there will always exist a solution to this equilibrium problem and the associated complementarity problem. The resulting inverse linear demand curve from the consumer's optimization problem

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[2] We calculate end-use costs as in Huppmann and Egging (2014).

allows for zero consumption, ensuring that there always exists a solution even under restrictive link capacities

Since our problem is formulated as a complementarity problem after taking first-order conditions, many of the welfare and profit related bilinearities (prices multiplied by quantities) do not exist in our equations. However, there could be other situations, such as completely rational models, where these nonlinearities exist in the optimization problem and consequently increase its computational complexity. These nonlinearities can be resolved by discretizing the problem Gabriel and Leuthold (2010), or using other techniques that resolve bilinear terms Gabriel et al (2013b); Mitsos et al (2009). The computational burden of these problems is orders of magnitude higher, and in many instances we are not guaranteed global optimality Siddiqui and Gabriel (2013). The multimodal flow aspect of the problem under social welfare optimization would also have to resolve these nonlinearities, but the structure could be formulated in the same way here.

3 The North American crude oil model—NACOM

3.1 Motivation for application to North American market

The United States experienced a major upsurge in the production of crude oil and natural gas over the past decade (see Figure 1). This has been largely attributed to advancements in hydraulic fracturing among other technologies that have 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 (Medlock et al, 2014; Medlock, 2012; Siddiqui and Gabriel, 2013) but economic-engineering modeling of the crude oil sector has received less attention in the academic literature to date. The epicenter of the shale oil revolution[3] can be found in the Bakken formation (North Dakota), with significant contributions from the Permian Basin (Texas, New Mexico) (Neff and Coleman, 2014). Heavy oil production has also been expanding across North America, particularly in Canada (Brady et al, 2015; Hofman and Li, 2009). 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.[4] A major consequence of the increased demand on rail infrastructure has been the rise of crude oil accidents. Although pipelines spill more gallons per incident, crude-by-rail spills have had more devastating impacts, as the rail lines often run near 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 the North American Crude Oil Model (NACOM)—an application of the multimodal equilibrium model introduced in Section 2. NACOM enables us to

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[3] Kilian (2014) provides a comprehensive background on the effects of this "shale revolution" on prices and infrastructure in the US.

[4] National Energy Board, "Canadian crude oil exports by rail—quarterly data": https://www.neb-one.gc.ca/nrg/sttstc/crdlndptrlmprdct/stt/cndncrdlxprtsrl-eng.html.
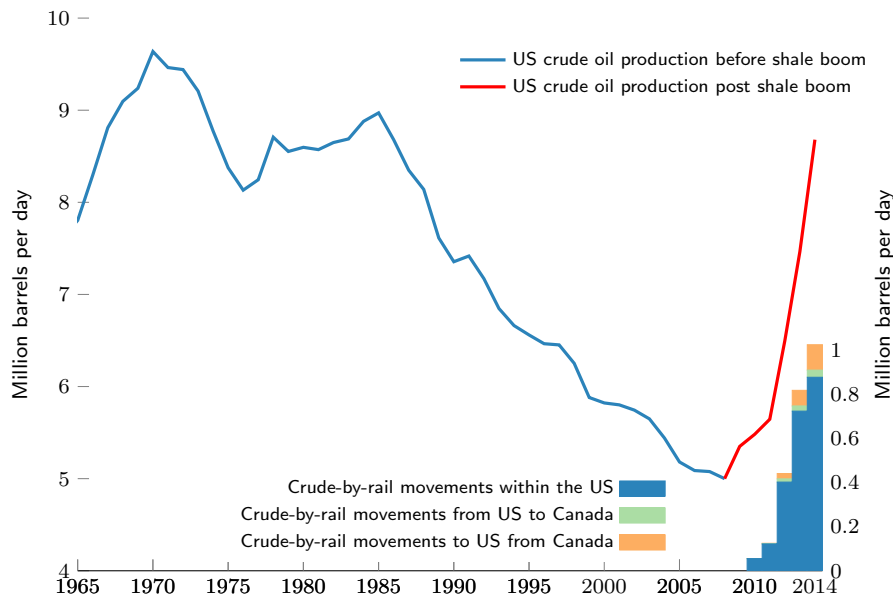
Fig. 1 US crude oil field production from 1965 through 2014. US/Canada rail movements of crude oil from 2010 to 2014 are juxtaposed to highlight their growth under recent production trends. (Data source: EIA)

study the flow of oil from the production fields to refineries across the various modes of transportation in North America while exploring player interactions. 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 time periods considered in this model are 2012, 2015 and 2018. To account for differences in crude oil qualities, we consider light-sweet and heavy-crude oil types. The implications of this differentiation are significant as refining and transportation capacities are specific to the crude oil type in consideration.

3.2 Review of relevant crude oil modeling work

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 (1974) 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 (2002) 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 (2015), which they used to explore the impact of supplier diversification on oil importer profits. Huppmann and Holz (2012) 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. Most

recently, Langer et al (2016) 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 (1988) developed a linear model for the US oil market in order to examine the effects of price on imports. In a new and relevant effort, Covert and Kellogg (2017) estimate a pipeline investment model to determine the elasticity of pipeline capacity to crude-by-rail shipment costs. However, no modeling attempt with multimodal flow granularity by US state and distinction by crude quality in the North American oil market currently exists in the academic literature. This application is therefore a major contribution in this regard, as we simulate the resulting market equilibria under a range of different policy measures over the medium term. 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 assembly and processing, 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.

3.3 Key features and data summary

As the first multimodal crude oil model, NACOM also notably features granularity at the US state level and Canadian regional level, while treating Mexico as a singular entity. The players are currently restricted to the suppliers, which are synonymous with the producing nodes, independent arc operators and refiners (demand nodes). We do not consider storage or transformation operators, as we limit consumption to the refining industry, excluding 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.

Data on US crude oil production and consumption (refining) were obtained from the Energy Information Administration (EIA).[5] Domestic supply and demand projections are given by the EIA's Annual Energy Outlook 2015 (EIA, 2015). Similar data for Canada were obtained both from the NEB[6] and CAPP.[7] Global supply and demand quantities and projections, including those for Mexico, were obtained from the International Energy Statistics on petroleum compiled

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[5] US Energy Information Administration, "Petroleum & other liquids": http://www.eia.gov/petroleum/data.cfm.

[6] Canada's National Energy Board: https://www.neb-one.gc.ca/nrg/sttstc/crdlndptrlmprdct/index-eng.html.

[7] Canadian Association of Petroleum Producers, http://www.capp.ca/publications-and-statistics/crude-oil-forecast

by the EIA.[8] 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 Material (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.

As production, transport and consumption figures for individual states (nodes) were not always readily available, regional data (by the PADD system[9]) 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 3.

Table 3 Regions and supply-demand nodes designated in NACOM

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

3.4 Crude oil production

The US has been a dominant player in the global crude oil market for many decades (Neff and Coleman, 2014). Production peaked in the 1970s, and the subsequent decline persisted until 2009 (see Figure 1). 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 (Levine et al, 2014). 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 (Kilian, 2014; Difiglio, 2014).

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

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[8] US Energy Information Administration, International Energy Statistics: http://tinyurl.com/gp3tb6b.

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

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)[10] (Zamora, 2014; Seelke et al, 2015). 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 (Zamora, 2014). The US is a major destination for Mexican crude, of which over 50% is of the heavy-sour grade (Seelke et al, 2015; Rana et al, 2007).
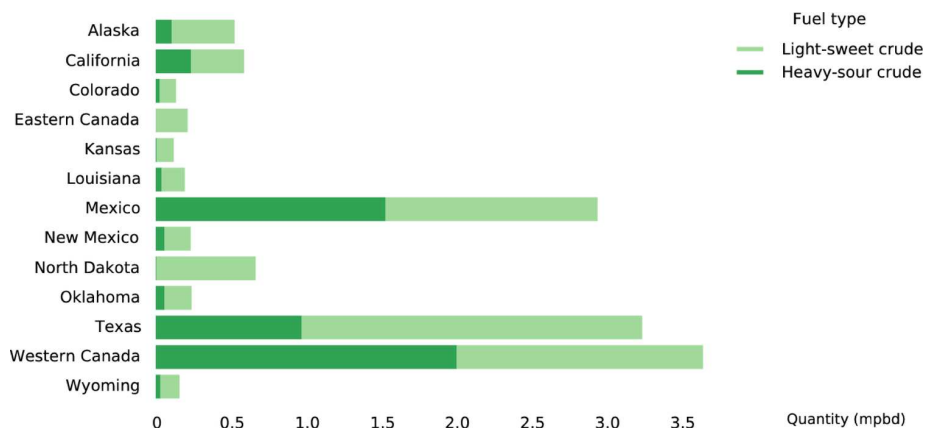
Fig. 2 Production (supply) nodes, showing split between light-sweet and heavy-sour crudes

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 2012, North Dakota and Texas were the fastest growing crude oil suppliers in the country (McFarland and Doggett, 2014). Figure 2 shows the 2012 quantities for the suppliers. Production for RW was excluded from this diagram for clarity.

3.5 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

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[10] Since 2013, Pemex has been in transition to involve private participation for better performance in the industry (Zamora, 2014).

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.[11] The demand quantities at each node are shown in Figure 3 for the base year 2012. The quantity for RW is again excluded here for the sake of clarity.
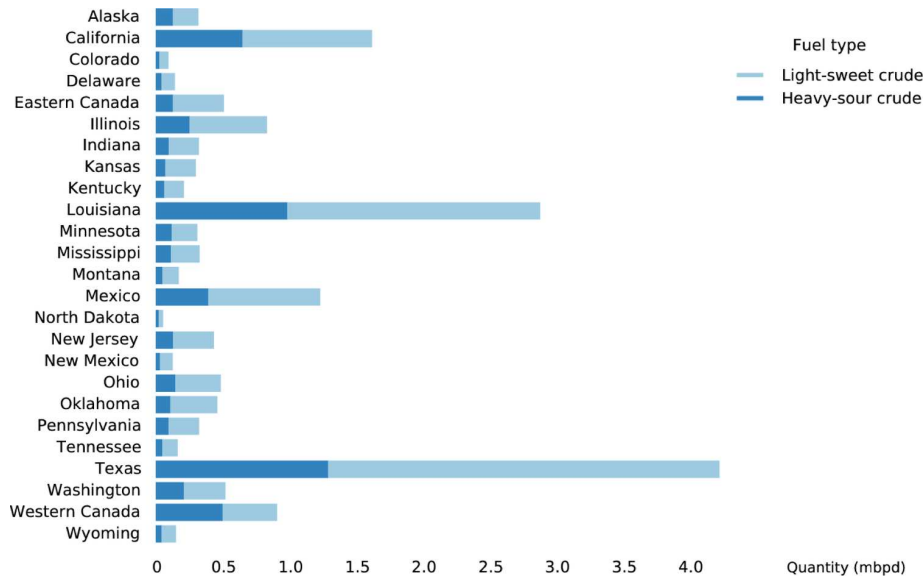

Fig. 3 Refining (demand) nodes, indicating yield of light-sweet crude to heavy-sour crude

3.6 Transportation

The transfer of crude oil from the oil fields and production sites to refiners both within and outside North America is multimodal by nature. In NACOM, we consider four distinct modes: rail, pipeline, river-going barge and ship (or tanker). The latter two modes comprise the waterway network: on water, tankers ply the sea routes while barges transport crude along the river system, of which the Mississippi is the most important. We do not consider the modal share of truckage, as it is relatively insignificant compared to the other two. 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.

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[11] Information on refining capacities from the Canadian Fuels Association: http://www.canadianfuels.ca/The-Fuels-Industry/Fuel-Production/.

3.6.1 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 1). 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.

The rail capacity data were obtained from a myriad of industry publications,[12] (as compiled by Oil Change International[13]). We aggregated the loading and unloading capacities of crude oil facilities 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.
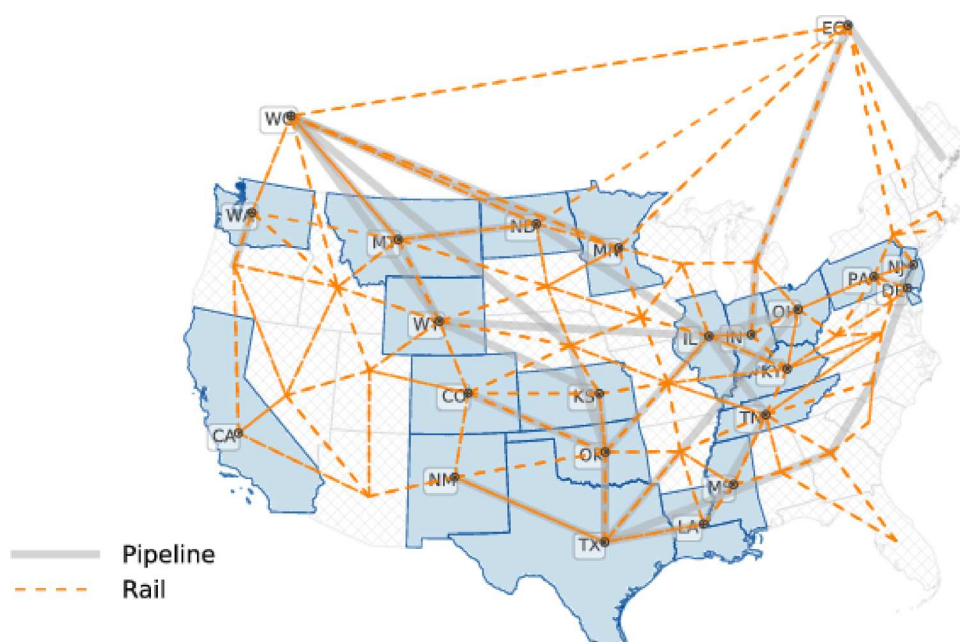

Fig. 4 Map of internodal rail and pipeline arcs in NACOM (not indicating directionality). The US states labeled are production or demand nodes. The waterway network, comprising inland (river, lake) and sea modes, is not shown in this figure but is still part of our model.

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

[13] North American crude-by-rail data available from Oil Change International at http://priceofoil.org/rail-map/.

3.6.2 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. The rate of increase in pipeline delivery in 2014 was also identical at 11.6% [14]. On average, pipelines have consistently accounted for 80% of the modeshare in crude oil transportation in the US since 2000 (Furchtgott-Roth, 2013). They are therefore a vital part of the crude oil infrastructure.

The process for gathering pipeline data began by consulting maps of established and functioning pipelines.[15] Most of the major pipelines in the US and Canada are owned by various private corporations.[16] 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 also shown in Figure 4.

On average, transporting crude oil via pipeline costs $5 per barrel (Fritelli et al, 2014). 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.

3.6.3 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 kbbl (thousand 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 kbbl (Fritelli, 2014). 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.

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[14] Pipeline delivery statistics are available from the 2014 and 2015 "US Liquids Pipeline Usage & Mileage Report" published by AOPL/API (Association of Oil Pipelines/American Petroleum Institute) at http://www.aopl.org/news-public-policy/reports-2/.

[15] These data were sourced from the Canadian Association of Petroleum Producers (CAPP, http://www.capp.ca/publications-and-statistics/crude-oil-forecast) and a compilation by P. Coutsoukis (http://www.theodora.com/pipelines/north_america_oil_gas_and_products_pipelines.html).

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

Due to the Jones Act, vessels shipping domestic crude oil must be built and owned by US interests (Fritelli, 2014). 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 (Fritelli, 2014).

Data on major inland routes were obtained from Fritelli (2014). 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.

3.7 Model calibration

Significant effort went into calibrating NACOM to produce results that matched observed quantities and prices for the base year of 2012. NACOM captured 82%, 85% and 91% of overall interregional rail, pipeline and waterway movements, respectively in 2012. Further calibration details and validation are provided in the Supplementary Material (Appendix A). We have calibrated NACOM 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.

3.8 Further note on data methods

As described in the preceding subsections, primary and related data on production, flows and consumption were obtained from a myriad of sources. While overall production and consumption figures and projections were straightforward to obtain for the nodes we considered, further work had to be done to obtain good estimates of production ratios and yield rates for the light-sweet and heavy-sour crude varieties. Comprehensive rail and pipeline data were not readily available from one single source, but we were able to generate the network for our model by aggregating and disaggregating arcs from maps and tables provided from various private and public sources as discussed. We assumed a linear relationship between arc costs and lengths. Pipelines or portions thereof supplying oil between points in the same US state or region were not explicitly modeled. Besides the tables detailing parameters for each node available in the Supplementary Material, spreadsheets of all our aggregate data and their respective sources, in addition to the Python scripts used for subsequent data handling and processing, are available at https://github.com/MODLJHU/nacom. These resources document and provide the requirements for reproducing the inputs to NACOM and can be readily modified to accommodate new data or developed for future work.

4 Results

We 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 present sensitivity results across four cases, and then 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.

Table 4 Sensitivity of model with respect to production costs

Case	Year	Production (million bpd)	Consumption (million bpd)	Flows (million bpd)	Revenues (million USD)	Benefits (million USD)
Base	2012	84.82	83.54	6.47	9.40	44.41
	2015	88.23	86.90	6.55	11.47	55.04
	2018	90.56	89.21	7.52	12.35	57.06
		percentage deviations from base case				
+5% costs	2015	−0.19%	−0.19%	−42.9%	0.18%	−0.16%
	2018	−0.03%	−0.03%	−32.1%	−0.56%	−0.07%
−5% costs	2015	2.82%	2.82%	19.2%	−5.39%	1.06%
	2018	3.15%	3.15%	32.1%	−5.89%	1.27%

4.1 Sensitivity analysis

To quantify the uncertainty in our model response, we study its sensitivity with respect to costs. In this analysis, we consider deviations of ±5% in all production cost terms. This results in two sensitivity cases to examine. We observe the output of the model in terms of total production, consumption, flows, revenues and consumer benefits. The flows taken into consideration are internodal, capturing the sum of inflows and outflows at all nodes. The corresponding percentage deviations for each of the cases are shown in Table 4. The results are also visualized in Figure 5 and Figure 6 to facilitate comparison across volumes (production, consumption, flows) and monetary amounts (revenues, benefits), for years 2015 and 2018, respectively.

    The results from this sensitivity test indicate that the model behaves as expected under this range of uncertainty. Production and consumption both decrease as expected for increased costs, and vice versa. Internodal flows vary more widely
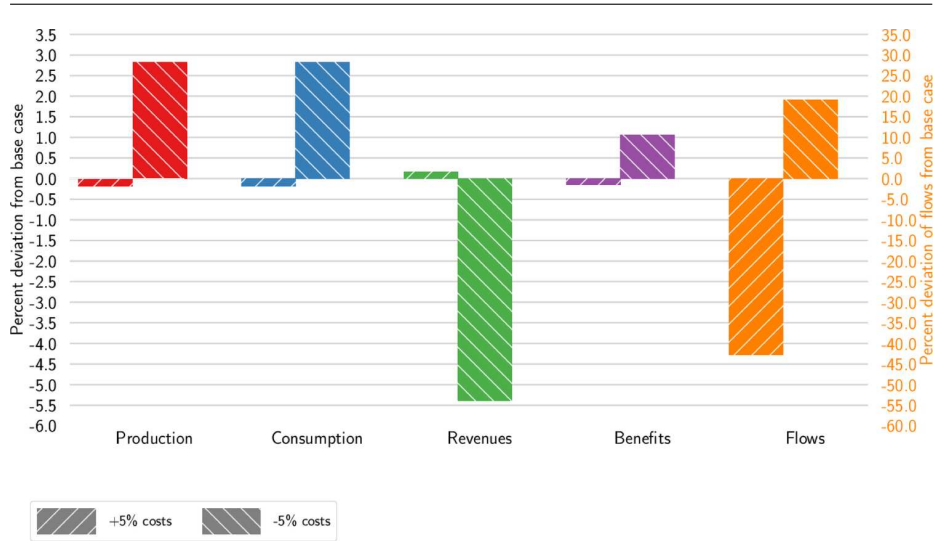
Fig. 5 Sensitivities of production, consumption, total revenues, consumer benefits and flow volumes in the system to cost for year 2015 ($\pm 5\%$ deviations in production costs).
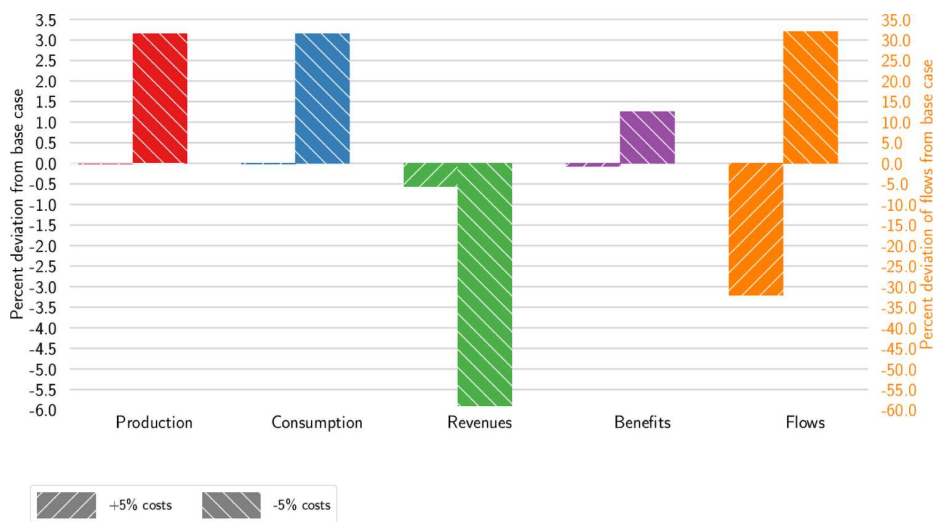

Fig. 6 Sensitivities of production, consumption, total revenues, consumer benefits and flow volumes in the system to cost for year 2018 ($\pm 5\%$ deviations in production costs).

in each of these sensitivity cases, however, but still in the expected direction. Revenues are less sensitive to increased costs, but decrease by around 5% for the "−5% costs" case. Welfare is the most inelastic outcome across both of the sensitivity cases examined.

4.2 The base case

Base case flows via rail and pipeline, according to the model, are depicted in Figure 7. 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.
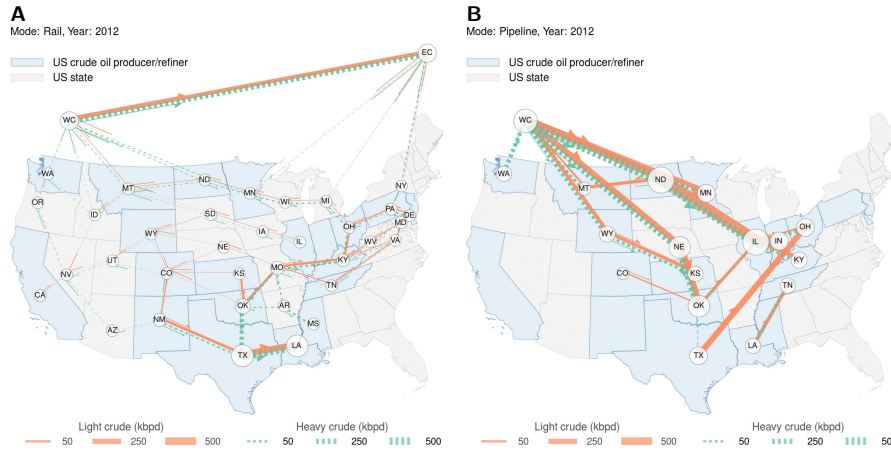

Fig. 7 (A) Rail movements and (B) Pipeline movements of crude oil in the base year 2012. The size of the node labels indicate the larger of the quantities of crude leaving or entering the respective node.

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.

4.3 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.[17] 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.[18] 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.[19]

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 8A, 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 8C, 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.

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[17] See 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/1HpU4El).

[18] This "Final Rule"—"Hazardous Materials: Enhanced Tank Car Standards and Operational Controls for High-Hazard Flammable Trains"—was developed in collaboration with the Pipeline and Hazardous Safety Administration in 2014. Available at http://federalregister.gov/r/2137-AE91 (Federal Register).

[19] See 2015 reports on the "oil train rules" by J. Mouawad at http://nyti.ms/1bmdr6G and http://nyti.ms/1AVFv7V.
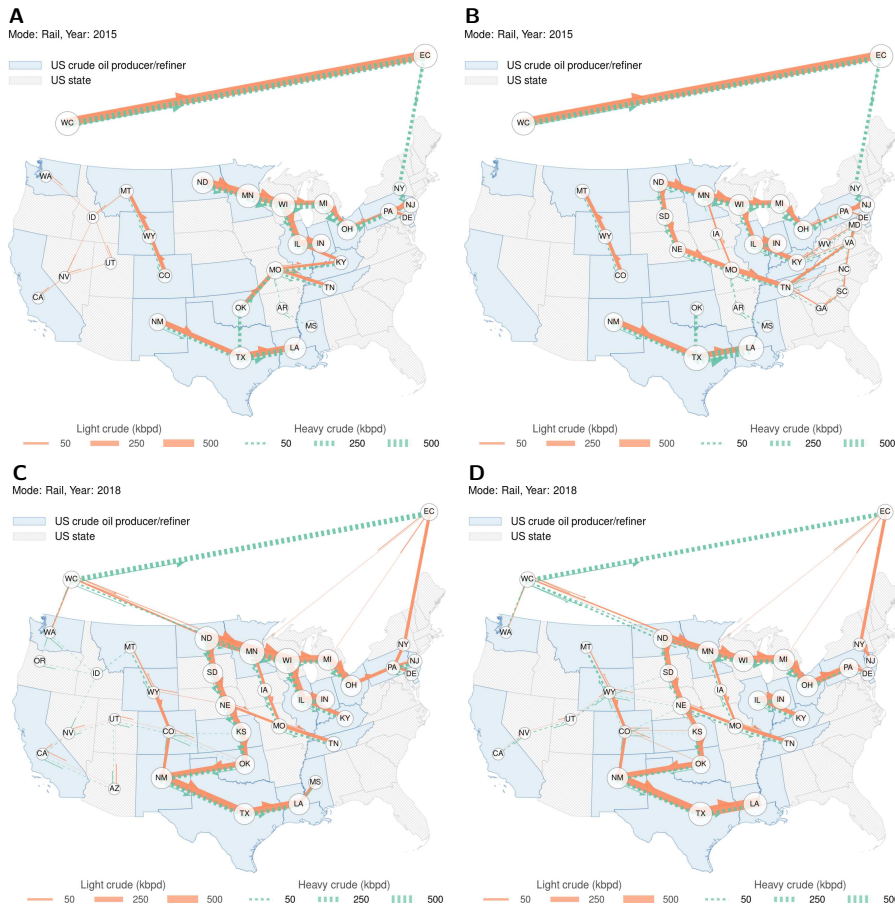
Fig. 8 (A) Rail flows in the base case, 2015 (B) 2015 rail flows in the scenario "Capping Rail Flows From Bakken Region" in which surrounding rail capacities are set to half of the base case flows through those arcs. (C) Rail flows in the base case, 2018 (D) Rail flows of crude oil in 2018 under the scenario "Capping Rail Flows From Bakken Region."

4.4 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 (Levine et al, 2014). 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.[20] 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,[21] 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.[22]
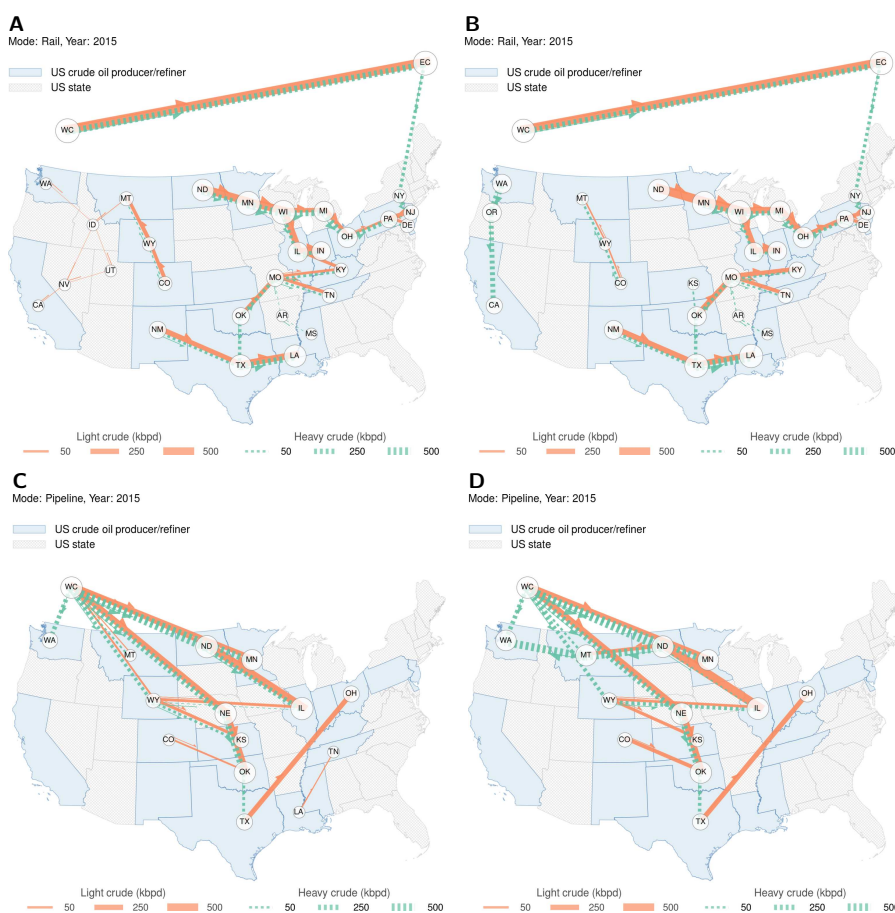

Fig. 9 (A) Rail flows in the base case, 2015 (B) 2015 rail flows in the scenario "US Midwest Pipeline Investments" in which new pipelines are built to convey oil from North Dakota both to the east and west. (C) Pipeline flows in the base case, 2015 (D) Pipeline flows of crude oil in 2015 under the scenario "US Midwest Pipeline Investments."

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[20] See New York Times report by C. Davenport, 2015, at http://nyti.ms/1MN5hpL.

[21] A description of the Energy East pipeline project is available from the NEB at http://bit.ly/1kBcNr1.

[22] See CBC News article, "Hydro-Québec raises concerns about Energy East pipeline," 2015 (http://bit.ly/1T5qgEa).

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.[23] The massive 30-inch 570 kbpd Dakota Access Pipeline (DAP) is also on track to come online toward the end of 2016.[24] The DAP will provide access to terminals in Illinois. Notably, TransCanada has also proposed the Upland Pipeline to carry up to 300 kbpd 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.[25]

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 kbpd of heavy-sour crude to the new Montana-Washington pipeline in 2015. In 2018, this pipeline carries 60 kbpd of heavy-sour crude and 131 kbpd 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 kbpd heavy-sour crude between Texas and Louisiana and also of 400 kbpd 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 kbpd to 7123 kbpd.

The newly added pipeline from Michigan to New Jersey, however, is left unused both in 2015 and 2018, 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 9.

4.5 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 (US Congress, 1975; Sheffield, 2014). 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 (Sheffield, 2014). National sentiment was therefore understandably in favor of shoring up reserves and increasing domestic supply.[26] Canada was exempt from this ban. Thus, any unrefined oil from the US invariably finds its way to Canada. Alaska had also been

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[23] See 2015 Bismark Tribune article by N. Smith at http://bit.ly/1jrcbEq

[24] See Bakken Magazine article for more information regarding the Dakota Access pipeline approval at http://bit.ly/1S8z8Gt.

[25] See CBC News report: B. Nicholson, J. MacPherson, "TransCanada to seek US approval for $600M Upland pipeline," 2015, at http://bit.ly/1VqYuGb.

[26] J. 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).

exempt from the ban since 1995, but its export volumes began to dwindle in the late 1990s.[27] Only in 2014, after a decade-long hiatus, did it send its first export shipment—784 kilobarrels to South Korea[28] (about 2 kbpd).

Considering the recent boom in US domestic production, the ban had been increasingly perceived to be more of a hindrance than a boon (Clayton, 2013). 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 (Sheffield, 2014; Duesterberg et al, 2014) 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.[29] 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.[30]

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 5).

Table 5 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

Notably, revenues rise significantly in regions with access to international markets. In particular, PADD5 (Alaska and California) indicates a 62% increase in revenues by 2018, thereby underlining why this is a future that would be favored by suppliers.

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[27] For a brief context on Alaska oil shipments, refer to J. A. Dlouhy's post at http://bit.ly/1WsVhou

[28] See Los Angeles Times report by M. Muskal, 2014, at http://fw.to/GFJiL7J

[29] Details 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.

[30] See Wall Street Journal report: K. Peterson, "Congress passes $1.15 trillion spending bill," 2015 (http://on.wsj.com/1OcL9hq)

Table 6 US regional revenues in the base case [BC] compared to those in the "US crude oil export ban lifted" scenario [EBL], for the years 2015 and 2018.

| Producing Region | 2015 | | | 2018 | | |
	BC (million USD)	EBL (million USD)	% gain	BC (million USD)	EBL (million USD)	% gain
PADD2	0.20	0.22	12	0.36	0.39	9
PADD4	0.35	0.04	14	0.03	0.03	11
PADD5	0.67	0.84	26	0.54	0.88	62

These movements, however, do not reduce the pressure on the rail network as intra-US flows increase 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.

4.6 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 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 7 shows the

Table 7 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

relative rail flow changes across the scenarios. The modal shares in each scenario are compared in Figure 10.

Table 8 and Table 9 detail the relative outcomes in revenues and consumer benefits (welfare), respectively, among the US nodes. The total revenues and welfare for the US, Canada and Mexico are shown in Figure 11 and Figure 12. In all the scenarios considered, there is no significant difference in welfare with respect to the base case. This would indicate that no one scenario has a particular advantage for the benefit of the refining sector. However, when revenues are taken into consideration, the combined strategy of exports, rail caps and pipeline investments outperforms the others in the medium term. Thus, this strategy emerges as the most robust given the desired outcomes of maximizing profits and welfare, while mitigating the environmental risk of crude-by-rail transport.

Further, 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.
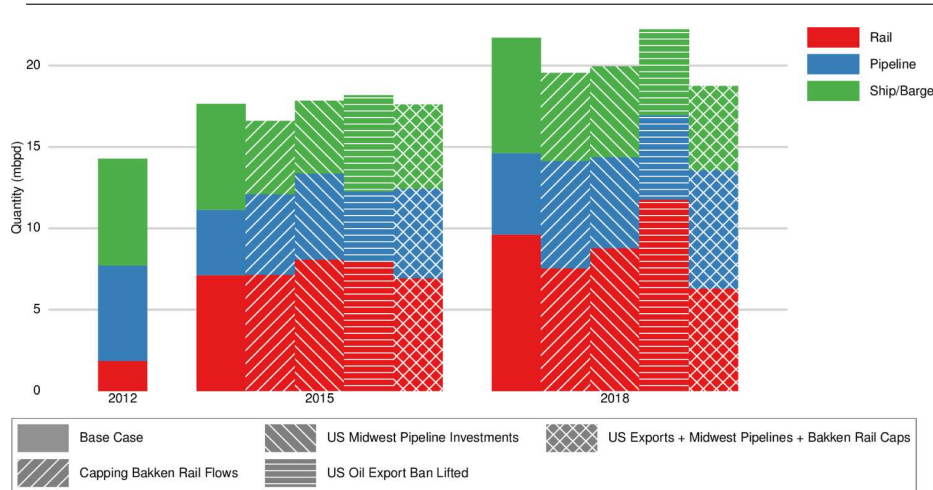
Fig. 10 Multimodal interstate (US) crude oil flows by scenario

Table 8 Changes in scenario revenues relative to the base case [BC] among the US nodes (states) in 2015 and 2018.

Scenario	2015		2018	
	Revenues (million USD)	% change	Revenues (million USD)	% change
Base Case	0.94	0	0.98	0
Capping Bakken Rail Flows	1.23	+31	1.24	+27
US Midwest Pipeline Investments	1.26	+34	1.22	+25
US Oil Export Ban Lifted	1.15	+22	1.35	+38
US Exports+Midwest Pipelines+Bakken Rail Caps	1.14	+21	1.37	+41

Table 9 Changes in scenario consumer benefits relative to the base case [BC] among the US nodes (states) in 2015 and 2018.

Scenario	2015		2018	
	Benefits (million USD)	% change	Benefits (million USD)	% change
Base Case	9.16	0	9.73	0
Capping Bakken Rail Flows	9.88	+1.50	11.01	+2.32
US Midwest Pipeline Investments	9.89	+1.66	11.00	+2.26
US Oil Export Ban Lifted	9.88	+1.59	10.98	+2.08
US Exports+Midwest Pipelines+Bakken Rail Caps	9.87	+1.47	10.97	+1.97

6 Future directions for NACOM

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 (Gordon et al, 2015). This would be valu-
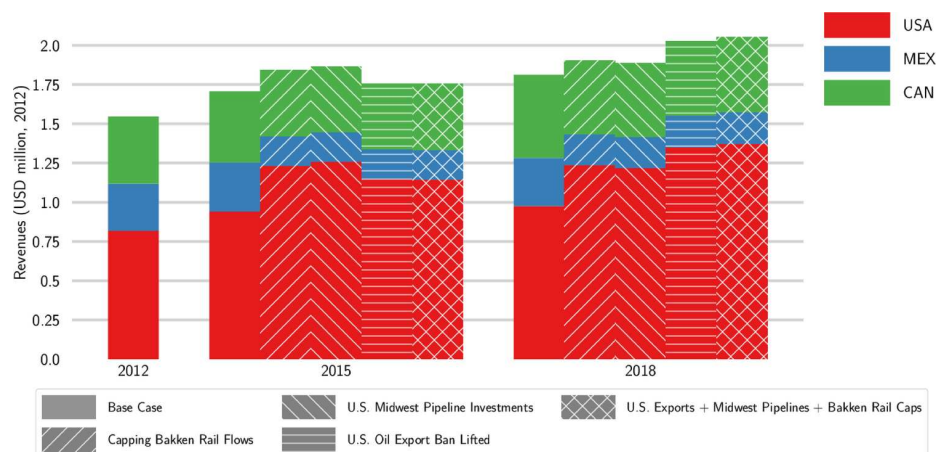
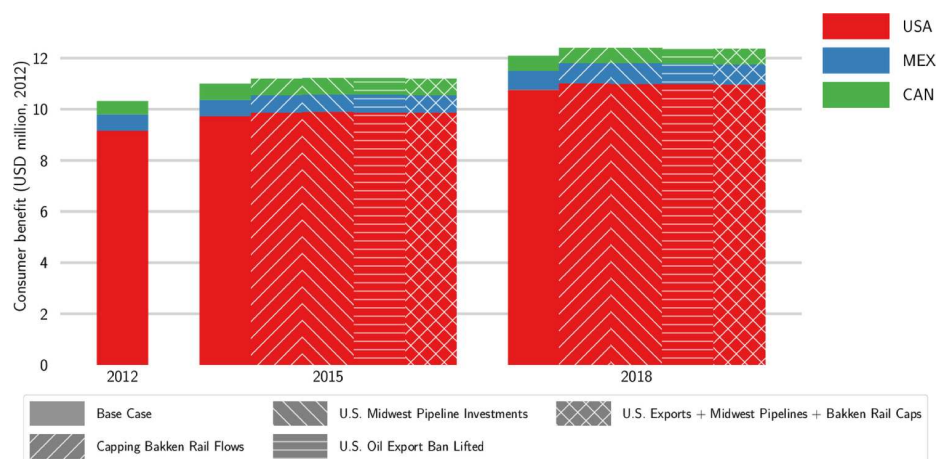**Fig. 11** Revenues in USA, Mexico and Canada by scenario. (Rest of World is excluded due to scale.)

Fig. 12 Consumer benefits in USA, Mexico and Canada by scenario. (Rest of World is excluded due to scale.)

able 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 supply 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.[31] Future work could incorporate these results along with the data also collected by Langer et al (2016) in their study.

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[31] Report, "Refining US Petroleum" (2015) available at https://www.afpm.org/uploadedFiles/Refining-US-Capacity.pdf.

At this stage of development, NACOM 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.[32] In recent years, storage has become a major concern in the industry as capacity is being stretched (Kilian, 2014; EIA, 2016). 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 that have been developed for natural gas (Feijoo et al, 2016) and bio-fuels (Christensen and Siddiqui, 2015; Siddiqui and Christensen, 2016) in North America. The strategic importance of the US in the global gas market is steadily rising (Medlock et al, 2014; Moryadee et al, 2014), even as it vigorously pursues a robust biofuel policy. The intersecting implications of these trends to climate, security, economy and industry are wide-ranging (Medlock, 2012; Victor et al, 2014; Morrison et al, 2014; Garcia et al, 2014). 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.

From the computational standpoint, each problem instance takes ∼13 minutes to solve in PATH (PATH 4.7.02; GAMS 23.9.5) using a 4GB Windows platform running on two 2.60GHz proccessor cores. Thus we propose, as an even more immediate direction of further development, a thorough characterization of the model structure. Such an effort would lend itself to further approaches for improvements in representation and reduction in problem size. Gains in efficiency of model implementation could be immediately realized in the performance of the PATH solver, as its parameters could be better tuned to harness the particularities of this MCP structure.

To strengthen the multimodal capabilities of our model, we would also like to account for interdependencies among the modes in the network. Incorporating these elements would extend the utility of the model for risk, failure and investment analyses, especially as they relate to the infrastructure on which the modes in consideration are reliant (Zhang et al, 2005; Gil et al, 2003). Finally, a stochastic extension to properly model the uncertainties of fuel transport (van Ruijven et al, 2010; Kannan et al, 2011) with regard to the mode of choice will simplify the calibration process and, more importantly, allow for more robust output and analyses.

7 Conclusion

We have presented a partial-equilibrium model for energy networks with multimodal flow capability. Our work builds on similar complementarity modeling efforts but its multimodal features are a novel contribution. This level of detail in modeling is increasingly critical to addressing the socio-environmental hazards

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[32] D. Murtaugh reports on current oil movement trends at LOOP in the Bloomberg article at http://bloom.bg/1zUyB7q.

arising from energy transfer processes within networks. To highlight the utility of our model in solving current energy network problems, we apply and calibrate this model to the crude oil market in North America. To this end, we developed the North American crude oil model (NACOM) with US state level granularity.

A medium-term model, NACOM is the first to capture the different modes of transportation and distinct crude oil qualities across the continent. Scenario analyses performed through NACOM indicate 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 solely lifting the export ban results in increased rail flows, a combination of export ban abolishment, pipeline investments and rail caps provides the lowest crude-by-rail flows in the medium term up to 2018, in addition to generating the highest revenues. 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 and its attendant safety and environmental risks.

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 (Salameh, 2003). In Canada, crude oil is still considered a mainstay of the nation's economy, as investments in production and transportation capacities continue to grow (NRCan, 2011; Hofman and Li, 2009). With proper reform, Mexico's oil industry can overcome current inefficiencies to transform its energy sector and economy (Seelke et al, 2015; Zamora, 2014). The recently approved crude oil swap between the US and Mexico is also expected to be mutually beneficial to US exporters and Mexico refiners (Breul and Brown, 2015). Given these trends, there will remain a need to find optimal intersections of policy and market decisions, not only for multimodal crude oil networks, but also for current energy systems and those of the future (Weijermars et al, 2012).

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Conflict of Interest: The authors declare that they have no conflict of interest.

Glossary

API	American Petroleum Institute
CAPP	Canadian Association of Petroleum Producers
EIA	Energy Information Administration (United States)
kbpd	thousand barrels per day
kbbl	thousand barrels
MCP	Mixed Complementarity Problem
mbpd	million barrels per day
NACOM	North American Crude Oil Model
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

A Supplementary material

A complete enumeration of the nodes and arcs, along with the flow calibration details of NACOM are provided in the Supplementary Material document available at https://github.com/MODLJHU/nacom. Data and processing code are also available for download at this location.

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