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Adding Alaska Petroleum Infrastructure to the National Transportation Fuel Model

Thomas F. Corbet, Sandia National Laboratories
Tatiana P. Flanagan, Sandia National Laboratories

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Thomas F. Corbet, Sandia National Laboratories, Policy and Decision Analytics
Tatiana P. Flanagan, Sandia National Laboratories, Resilience and Regulatory Effects

Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185

Abstract

Alaska oil fields provide an important, but diminishing, portion of the crude oil processed by Alaska and U.S. West Coast refineries. Production of crude oil in Alaska is being stressed by declining production in mature fields, high costs for developing and producing new fields, increasing competition from tight oil production in the Lower 48 states, and low global oil prices. The National Transportation Fuel Model is a network model of petroleum infrastructure in the Lower 48 states and portions of Canada developed at Sandia National Laboratories. It provides a simulation capability for analysis of system-wide responses to stressing events. Until now, however, this model did not explicitly include the petroleum infrastructure of Alaska and the transport of crude oil by marine shipments from Alaska to West Coast refineries. This paper describes the methods and information requirements for adding Alaska infrastructure to the National Transportation Fuel Model, provides an overview of the new Alaska portion of the model, and presents an example simulation of a closure of a large San Francisco refinery.

Acknowledgements

Evan James Frye, Energy Industry Analyst at the Office of Oil and Natural Gas within the U.S. Department of Energy Office of Fossil Energy, and Nancy Johnson, Director of Environmental Science and Policy Analysis, provided valuable information and insight into Alaska's petroleum industry, and provided suggestions for improving a draft of this paper. However, any errors or omissions are the sole responsibility of the authors.

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List of Acronyms and Abbreviations

DOE	Department of Energy
EIA	U.S. Energy Information Administration
NFTM	National Transportation Fuel Model
NISAC	National Infrastructure Simulation and Analysis Center
TAPS	Trans-Alaska Pipeline System

1 Introduction

Alaska produced an average of 483,000 barrels per day of crude oil in 2015[1]. Of this total, 96% was produced from North Slope oil fields. A small amount of North Slope oil is refined for local use in North Slope refineries, but most is transported on the Trans-Alaska Pipeline System (TAPS) to Alaska refineries and to the Port of Valdez where it is loaded on oil tanker ships for transport to refineries in California and Washington State. Production of crude oil on Alaska's North Slope is being stressed by declining production in mature fields, high costs for developing and producing new fields, increasing competition from tight oil production in the Lower 48 states, and low global oil prices. North Slope production peaked in 1988 at 2.0 million barrels per day and has been steadily declining since.[2] Declining production puts the TAPS at risk of flow rates declining below the rate required to keep oil in the pipeline sufficiently warm to prevent ice formation that could plug or damage pump equipment, deposition of wax that is dissolved in the crude oil at warmer temperatures, and other operational problems[3].

West Coast refineries are currently not connected by pipeline to major domestic oil producing regions. In addition to Alaska oil, they receive oil from California oil fields, water shipments from foreign sources, and more recently, rail shipments from North Dakota, which have partially offset the decline in production from Alaska and California[4]. Alaska provides an important, but diminishing, portion of the crude oil processed by West Coast refineries. In 2013, 46.2% of oil that came into Washington refineries was from Alaska, and 13.9% came from North Dakota. In contrast, 90% of crude came from Alaska in 2003, and no oil came from North Dakota[5]. The percentage of processed oil that was supplied from Alaska to California peaked from 1989 to 1991 at 46% and declined to 11.75% by 2015[6].The National Transportation Fuel Model (NTFM) was originally developed by the National Infrastructure Simulation and Analysis Center[7] (NISAC) as a network model of the transportation of crude oil and refined products in the Lower 48 states and portions of Canada. It provides a simulation capability for analysis of system-wide responses to stressing events. The Office of Oil and Natural Gas within the U.S. Department of Energy Office of Fossil Energy, recognizing the importance of simulating the strong interdependence between the Alaska oil production and transportation infrastructure and fuel supplies in the Lower 48 states, sponsored the addition of Alaska infrastructure and its ocean transportation connections to the NTFM.

[1] U.S. Energy Information Administration, "Alaska Field Production of Crude Oil," http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=MCRFPAK2&f=A.

[2] U.S. Energy Information Administration, 2012, "Projected Alaska North Slope oil production at risk beyond 2025 if oil prices drop sharply," http://www.eia.gov/todayinenergy/detail.cfm?id=7970.

[3] "2014 Annual Report," State Pipeline Coordinators Office, Alaska Department of Natural Resources, 68p.

[4] U.S. Energy Information Administration, 2014, Crude-by-rail transportation provides Bakken Shale production access to major markets, http://www.eia.gov/todayinenergy/detail.cfm?id=16631.

[5] Washington Research Council, 2013, "The Economic Contribution of Washington State's Petroleum Refining Industry in 2013," https://www.wspa.org/sites/default/files/uploads/WRC - 2014 Refinery Report Final 122214.pdf.

[6] California Energy Commission, "Oil Supply Sources to California Refineries," http://www.energy.ca.gov/almanac/petroleum_data/statistics/crude_oil_receipts.html.

[7] NISAC is a program of the U.S. Department of Homeland Security, National Protection and Programs Directorate's (NPPD) Office of Cyber and Infrastructure Analysis (OCIA)

The fuel supply infrastructure represented by the NTFM spans from oil fields to fuel distribution terminals. This includes the business activities of producing crude oil from oil wells, transporting (gathering) the oil from individual oil wells to storage tanks in or near to oil fields, transporting crude oil from the oil field storage sites to refineries, the refining process, and transporting refined products to distribution terminals. Refineries process crude oil to produce refined products. Although there are other categories of refined products, this report considers only gasoline, jet fuel, and distillate (including diesel fuel). Long-distance high-volume transport of crude oil and refined products by pipeline, rail, or water shipments is referred to as transmission. Distribution terminals are at the downstream end of the refined product transmission system. Terminals consist of tank storage and equipment (truck racks) for blending fuels and loading trucks that deliver fuel to retail stores.

Infrastructure is represented as a network (Figure 1) consisting of oil fields, refineries, tank farms, ports, and terminals (the nodes of the network), and the pipelines, rail lines, and waterways that connect the nodes (the links of the network). The designed use of the NTFM is to 1) calculate undisturbed (steady-state) operation of the present-day petroleum supply network, and 2) simulate how that network performs given specified disruptions to infrastructure components. Simulations represent dynamic market-driven adaptive responses including: drawing down inventories at storage and distribution terminals, increasing utilization of undisrupted infrastructure components, rerouting flows on transportation systems, and decreasing consumption of fuels in regions where availability is reduced. See Wilson et al., 2015[8], for an overview of the modeling approach and example simulations, and Beyeler et al., 2012[9], for details of the flow algorithms.

[8] Wilson, Michael L., Thomas F. Corbet, Arnold B. Baker, and Julia M. O'Rourke, 2015, "Simulating Impacts of Disruptions to Liquid Fuels Infrastructure," Sandia National Laboratories, SAND2055-2696, 57p.
[9] Beyeler, Walter E., Thomas F. Corbet Jr., and Jacob A. Hobbs, 2012, "A Demand-driven, Capacity-constrained, Adaptive Algorithm for Computing Steady-state and Transient Flows in a Petroleum Transportation Network," Sandia National Laboratories, SAND2012-9487, 15p.

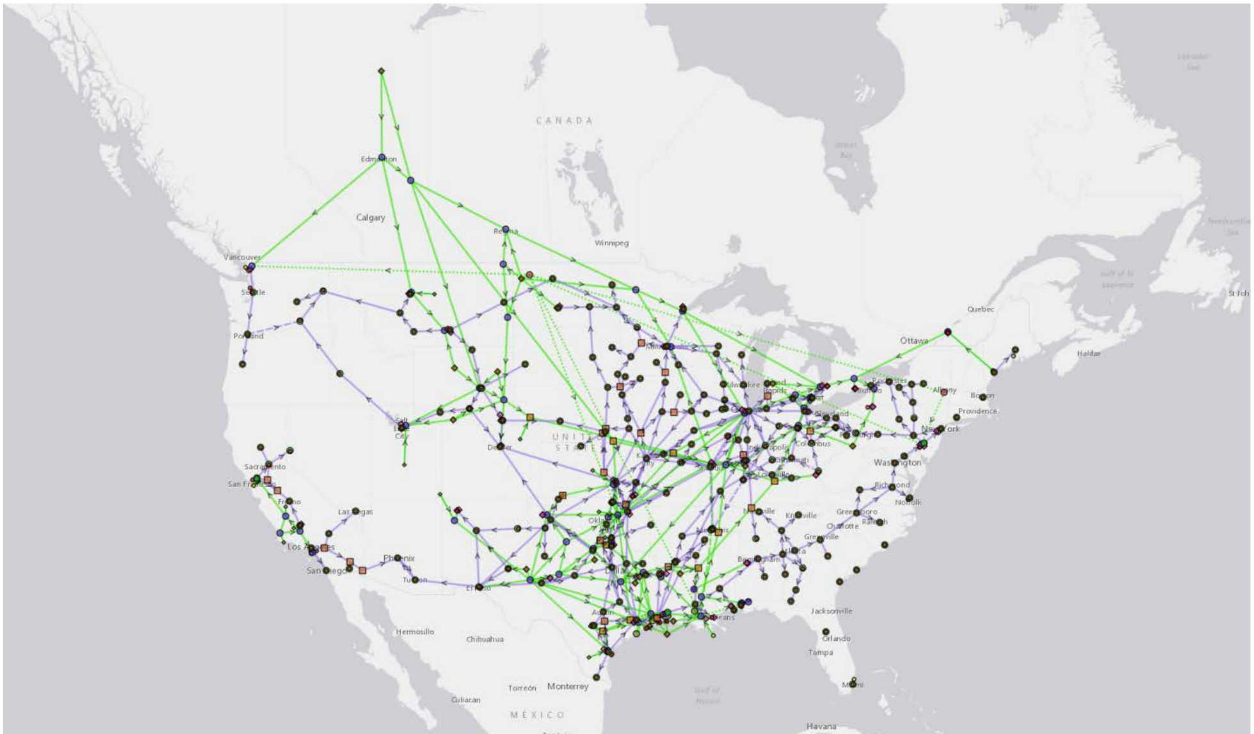

Figure 1. National Transportation Fuel Model (Version 2.2) network. Green links represent crude oil transmission pipelines and rail transportation. Purple links represent refined product pipelines.

Previously, the interdependence of Alaska oil production and U.S.-refined product supplies was represented in the NTFM (Version 2.2) only conceptually, in that it was recognized that a portion of the simulated receipts of crude oil at West-Coast ports originated in Alaska. These receipts were treated simply as lumped sources of crude oil to the model network without specifications of the origins of the oil or the fraction supplied from each origin. Also, Alaska infrastructure was completely absent from the NTFM network. Adding Alaska to the NTFM network increases the range of application by adding the capability to simulate:

- impacts of disruptions to specified infrastructure components in Alaska on fuel availability and inventories in the Alaska and the Lower 48 states,
- impacts of disruptions to West Coast infrastructure on Alaskan inventories and oil field production, and
- dynamics of competition between suppliers of crude oil to the West-Coast refineries during disruptions.

This paper describes methods and information sources for Alaska infrastructure in the NTFM, provides an overview of the new Alaska portion of the model, and presents an example simulation of a closure of a large San Francisco refinery.

2 Methodology

The NTFM is essentially a database containing a description of the model network nodes and links and their connectivity and properties. The nodes represent oil producing areas, refining complexes, tank farms, terminals, and ports. The links represent transportation of crude oil or refined products. Transportation in NTFM is by transmission pipelines, rail, and water-borne shipments. NetFlow Dynamics is a web-based, network-modeling environment developed at Sandia National Laboratories. It contains the flow algorithms, geographic information system-based visualization, and database editing capabilities used to update the NTFM, perform simulations, and analyze simulation results.

A new version of the NTFM (Version 2.4) was developed by 1) adding nodes and links representing Alaska infrastructure to the previous version 2.2, 2) adding links representing water shipments to West Coast ports, and 3) calculating the undisturbed flows in the new parts of the model network including production of crude oil from each active lease unit, throughputs of Alaskan refineries, and average flow rates on pipelines, a rail line, and shipping routes to three West-Coast ports. We expect these changes to be a permanent feature of future versions of the NTFM. For consistency with the previous version of the NTFM, the new portions of the network have properties representing conditions as of the end of calendar year 2013. Tasks 1 and 2 are the process by which information and data about the actual infrastructure is compiled into a model network. Task 3 is a computational effort performed by the algorithms in NetFlow Dynamics.

Tasks 2 and 3 require that the connectivity and capacity of network elements are specified in the NTFM database. Specified capacities include the flow capacity of individual pipelines, rail lines, and shipping routes, the production capacity of oil fields, the throughput capacity of refineries, and the volume capacities of storage sites at tank farms, terminals, and ports. It is also necessary to specify the fraction of volume capacity utilized at each storage site during normal operations. This fraction acts a target level of inventory that the flow algorithm strives to achieve if there is a sufficient supply of crude oil or refined product. Although not required as part of the model network specification, it is desirable to have information about actual average flows or inventory levels to aid in calibrating calculated flows and levels.

Typically only some of the capacity values listed above are publically available, and those that are available most be compiled from disparate sources. The NTFM uses data from a variety of sources. The model network was updated recently to represent the state of infrastructure at the end of 2013, the most recent time period for which sufficient information was available at the time of the update. This update includes information provided by INTEK Inc. for recent pipeline changes and rail loading/unloading capacities of crude, and information provided by the Energy Information Administration (EIA) on recent rates of crude-oil production at model nodes that represent producing regions. Import and export data at various ports and amounts of petroleum transportation on rivers are taken from calendar year (CY) 2012 data collected by the U.S. Army Corps of Engineers Waterborne Commerce Statistics Center. Crude production, refinery capacities, and storage are from CY 2013 data provided by the EIA. The service areas for the aggregated distribution terminals, as well as the amount of demand for each area, are estimated from 2012 U.S. Census Bureau and 2013 EIA data. Information on pipeline capacities came from a wide variety of sources, including geographical information system (GIS) databases, company reports, web sites, news articles, and a 1989 study by the National Petroleum Council.[10]

[10] National Petroleum Council, *Petroleum Storage and Transportation*, 5 volumes, 1989.

3 Model Description

The Alaska portion of the NTFM Version 2.4 represents, and connects, oil production on the North Slope and in the Cook Inlet; refineries in the Cook Inlet, the Fairbanks area, and at Valdez; the TAPS pipeline system and the Valdez Terminal; rail transportation of refined products from Anchorage to Fairbanks, and water shipments of crude oil to West Coast refineries in Washington State, San Francisco, and Los Angeles. Figure 2 shows a statewide view of the NTFM network, and Figure 3 shows pipelines and oil production areas on the North Slope. All labeled items in Figure 3 are lease units except for two small refineries. Lease units that are not connected to pipelines are not currently producing crude oil. They have been included in the model network for possible future use.

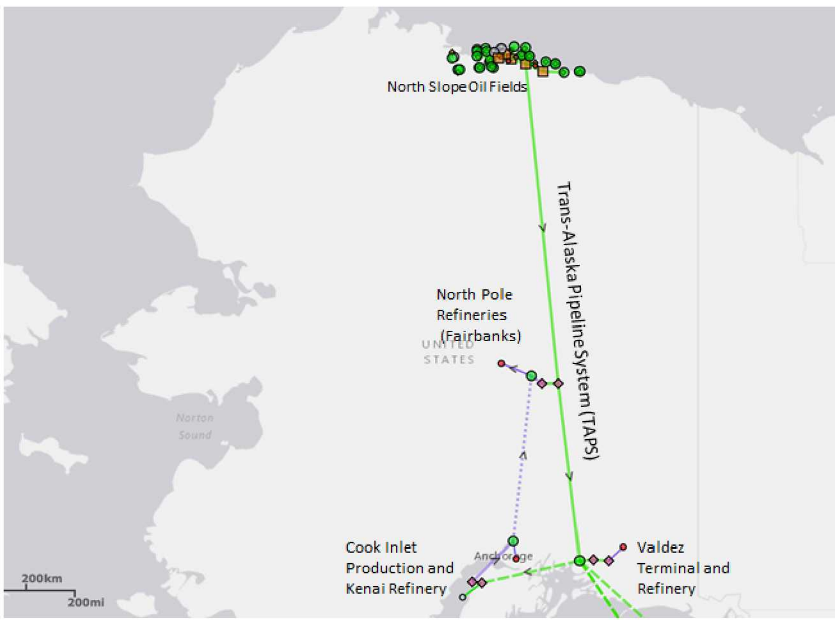

Figure 2. Alaska portion of the National Transportation Fuel Model (Version 2.4). Solid green links represent crude oil transmission pipelines; dashed green links represent water transportation of crude oil. The solid purple link is a refined product pipeline; the dashed purple line represents rail transportation of refined products.

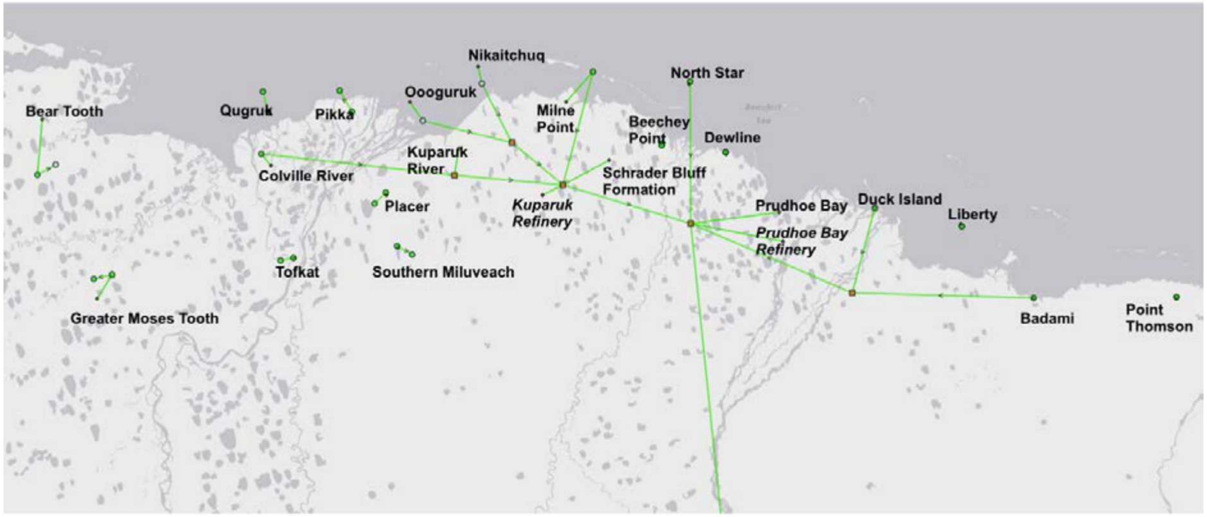

Figure 3. Detail of North Slope infrastructure and oil fields.

Water shipments from Valdez to West Coast refineries are represented as three separate model links, one to each of Washington State, San Francisco, and Los Angles (Figure 4).

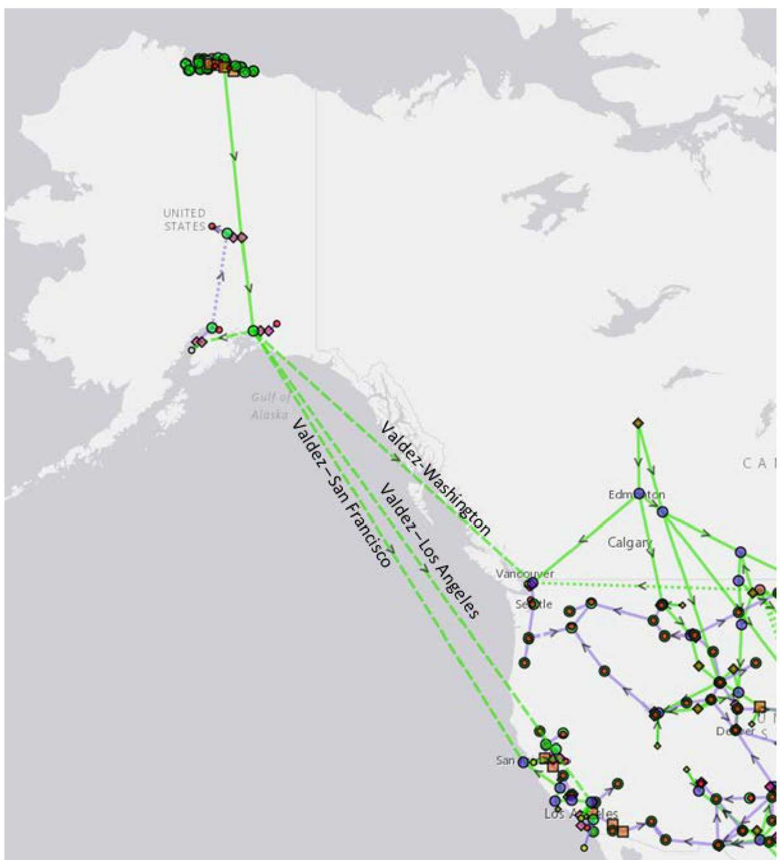

Figure 4. The Alaska portion of the NTFM connects to the rest of the model via three links representing water shipments of crude oil to West Coast refineries.

There are several notable assumptions and limitations of the new Alaska portion of the NTFM:

- The refined product distribution system is not represented in detail. Intra-state water shipments of refined products are not explicitly represented in the model network. Alaska consumption of refined products is aggregated at terminals in Anchorage and Fairbanks, and at the Petro Star Valdez Refinery. The small amount of refined products that are transferred to and from the Lower 48 states is not included.

- Refinery throughput is estimated to be a percentage of refinery capacity.

- Currently, we know the amount of Alaska oil that ships to California and Washington, but not the fraction that ships to individual California refining centers.

4 Scenario disruption

We present a simulation of a California refinery disruption as an example of the interdependencies between Alaska petroleum infrastructure and the West Coast transportation fuel market. Specifically we simulate a 60-day closure of the Richmond refinery in the San Francisco area. There are five refineries in the San Francisco area with a total capacity of 820 thousand barrels per day. The Richmond refinery provides 245,000 barrels per day of this total capacity[11]. The San Francisco refineries serve consumers in northern California and northern Nevada. A smaller portion of the San Francisco refineries output is transported by marine shipments out of San Francisco ports to other West Coast ports, or is exported.

This scenario disruption has cascading impacts both downstream to consumers of refined products and, by reducing demand for crude oil, to upstream to crude suppliers, including Alaska. Because the suppliers of crude oil to San Francisco refineries also supply refineries in other West-Coast cities, we expect that there would be market competition for each crude oil supplier to increase shipments to these other refineries.

Simulation results are best viewed interactively from within NetFlow Dynamics graphical interface, but here we show images captured from the interface screen. First, we present selected graphs showing how simulated flow rates upstream and downstream from San Francisco change with time. We then zoom out to show the geographical extent of impacts. Although, we present only results at selected points in the supply network, the NetFlow Dynamics algorithms calculate flow rates and inventory levels for each component of the network. The algorithms are designed specifically to simulate the cascading dynamics that cause impacts of a disruptive event to be felt at different magnitudes and different times at each point in the network. The variation in magnitude and timing of impact is due mainly to the degree that a particular point is connected to other parts of the network and the amount of inventory that is available to delay fuel shortages. Details of the computational algorithms are beyond the scope of this paper, but are available in Beyeler et al., 2012[12].

The orange line (Figure 5) shows the total refining capacity of the five San Francisco refineries over time. This refining-capacity graph is the only input to this scenario simulation. All other results are the outputs of the simulation. Input for simulations of more complex events such hurricanes or earthquakes typically involve specifying capacity reductions of individual pipelines, refineries, oil fields, and other infrastructure elements. Schedules for recovering reduced capacity are typically more complex than the simple square-wave function used in this example. Refinery capacity is reduced, starting at simulation day 10, from 820,000 to 575,000 barrels per day for 60 days representing the closure of the Richmond refinery. The blue line shows the total simulated output of the refineries. Before the refinery closure, the total output of the refineries is running at about 89% of capacity. At the time of the closure, total output falls below the new lower capacity because it

[11] EIA, 2014 Refinery Capacity Report, Table 3, “Capacity of Operable Petroleum Refineries by State as of January 1, 2014.”

[12] Beyeler, Walter E., Thomas F. Corbet Jr., and Jacob A. Hobbs, 2012. A Demand-driven, Capacity-constrained, Adaptive Algorithm for Computing Steady-state and Transient Flows in a Petroleum Transportation Network, Sandia National laboratories, SAND2012-9487, 15p.

takes some time for the other refineries to ramp up production. When the refinery re-opens, total output quickly rises to a level higher than pre-closure rates as the supply network strives to replenish refined product inventories. Total output returns to pre-closure rates about 85 days after the refinery re-opens.

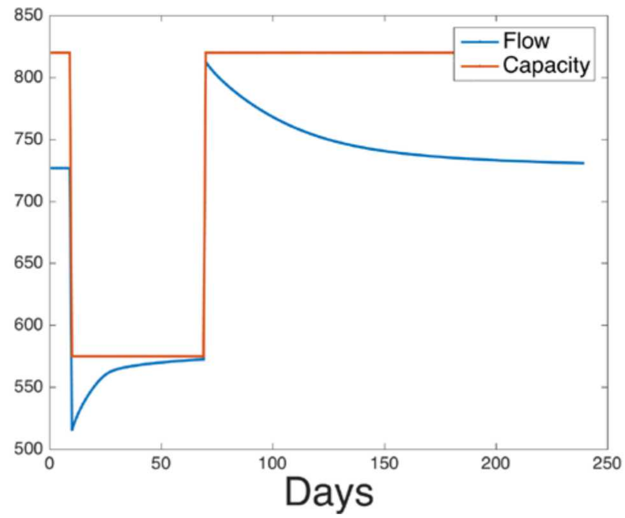

Figure 5. Refining capacity (orange), and simulated refinery throughput (blue) in thousands of barrels per day, with respect to time for San Francisco area refineries.

The decreased output of the refineries results in a drawdown of refined products inventories in San Francisco terminals, but an increase of crude oil inventory (Figure 6 and Figure 7).

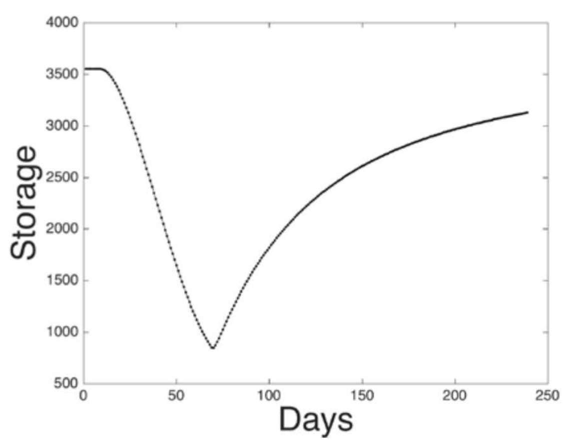

Figure 6. Simulated refined product inventory, in thousands of barrels, with respect to time, at San Francisco area terminals.

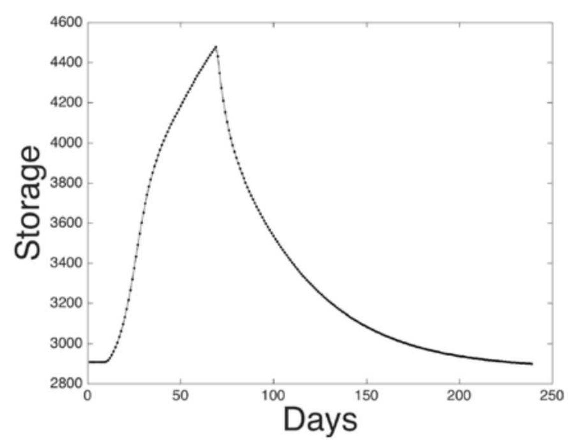

Figure 7. Simulated crude oil inventory, in thousands of barrels, with respect to time, at San Francisco area terminals.

The reduced supply of refined products cascades downstream along transmission pipelines to, for example, Sacramento. Simulated fuel consumption in Sacramento slowly decreases (Figure 8) by about 4,000 barrels per day (about 2.5 percent of normal consumption) over 85 days, perhaps making the governor mad. Although NetFlow Dynamics does not explicitly calculate fuel prices, this behavior of decreasing fuel consumption when supplies are tight is a proxy for the price elasticity of demand.

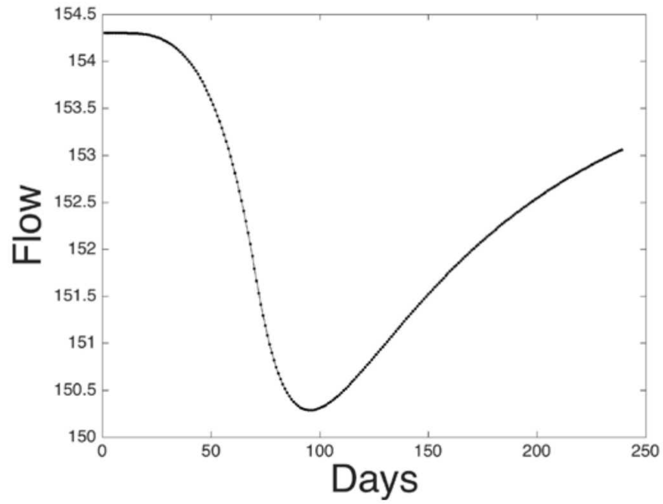

Figure 8. Simulated refined product consumption, in thousands of barrels per day, with respect to time, in the Sacramento area.

Looking upstream toward Alaska, the glut of in the San Francisco area reduces the demand for receipts of water shipments and consequently, crude oil shipments from Valdez to San Francisco decline (Figure 9).

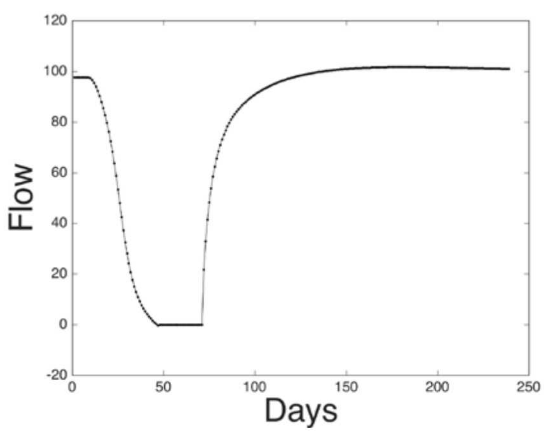

Figure 9. Simulated crude oil shipments from Valdez to San Francisco, with time.

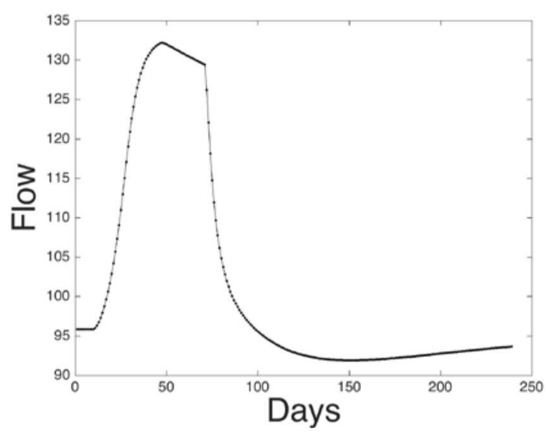

Figure 10. Simulated crude oil shipments from Valdez to Los Angeles with time.

However, market dynamics allow Alaska producers to gain a larger share of the supply to Los Angeles and Washington refineries. Figure 10 shows the resulting simulated increase in shipments from Valdez to Los Angles, at the expense of other suppliers of crude oil to Los Angeles.

Even with increased shipments to Los Angles and Washington, the net crude shipments from Valdez at the end of the refinery closure are about 27,000 barrels per day less than before the closure. This net reduction in shipments cascading throughout Alaska oil infrastructure results in increased inventory at the Valdez terminal (Figure 11), lower flow rates on the northern portion of the TAPS (Figure 12), and ultimately reduced production from the Prudhoe Bay field (Figure 13).

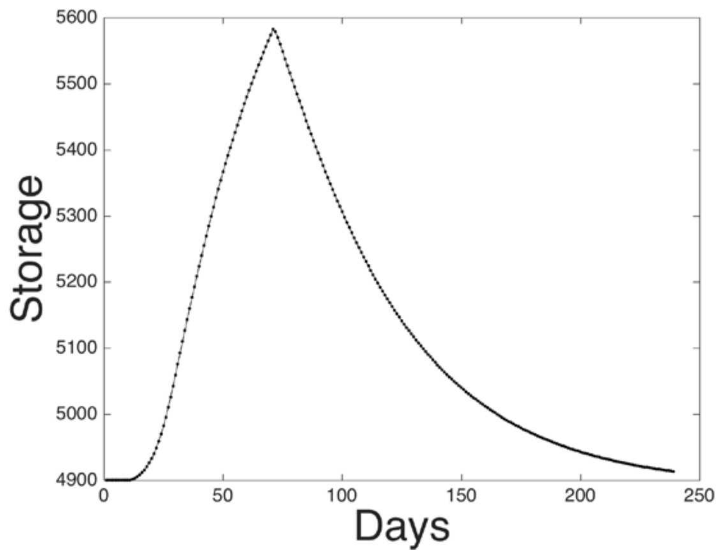

Figure 11. Simulated crude oil inventory, in thousands of barrels, with respect to time at Valdez.

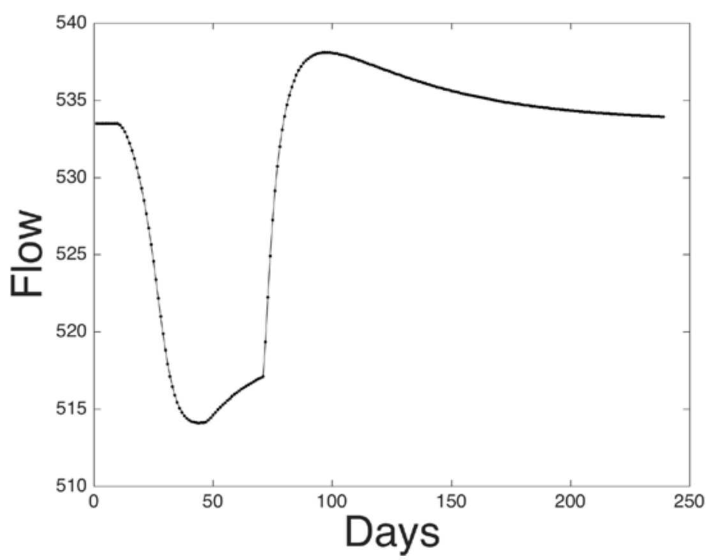

Figure 12. Simulated flow of crude oil, in thousands of barrels per day, with respect to time on the northern section of the TAPS.

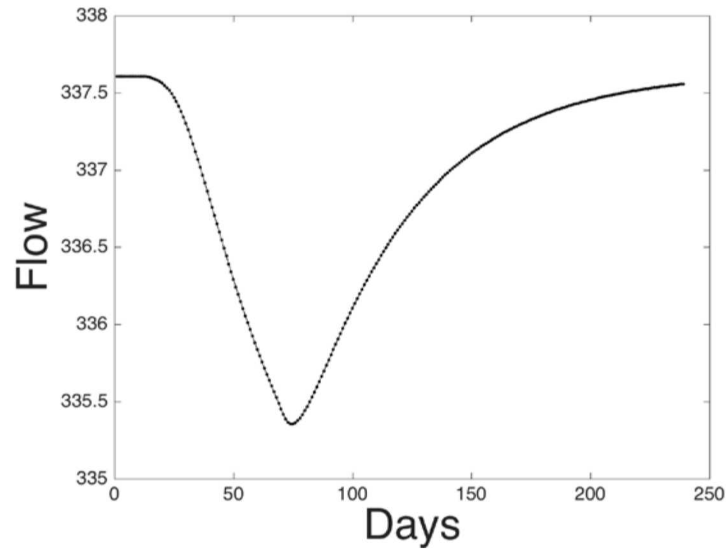

Figure 13. Simulated production of crude oil, in thousands of barrels per day, with respect to time at the Prudhoe Bay field.

Figure 14 shows simulated flow rates on the last day of the refinery closure. Only portions of the model network that changed by more than 1.0% relative to pre-closure conditions are shown. The major changes are increased flow of Alaska crude oil to Washington and Los Angles, decreased flow of Canadian crude to Washington, and decreased flow on the TAPS. The yellow shaded area shows where fuel shortages occur.

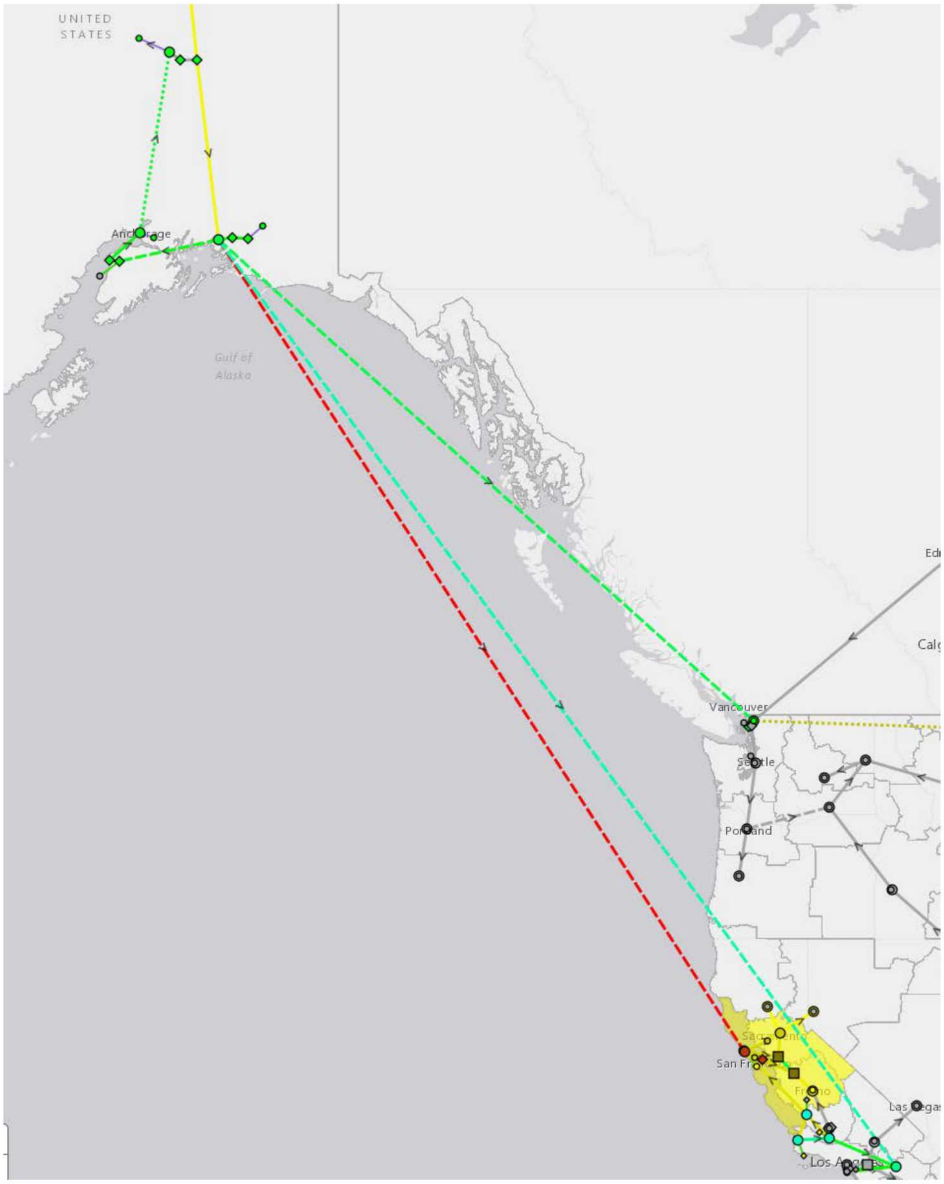

Figure 14. Simulated changes in flow rates at the end of the refinery closure. Yellow indicates a relatively small decrease relative to pre-closure, red, a larger decrease, and green indicates an increase in flow.

The simulation results presented here are intended to demonstrate the types of cascading impacts that could be investigated using the revised version of the NTFM with Alaska connected. However, these results are not intended to be a quantitative analysis of the simulated scenario because only a single set of values for uncertain parameters was used. There are two categories of uncertainties: those that pertain to the properties and level of aggregation in describing the physical infrastructure in the NTFM model network, and those that are embedded in the NetFlow Dynamics algorithms that pertain to the assumptions about how consumers and infrastructure operators respond to the scenario disruption. Here we provide a brief discussion of the key uncertainties in the second category.

One important assumption of the flow algorithm is that all types of crude oil and all types of refined products are fungible. Crude oil is classified by its density and Sulphur content. For example, Alaska mainly produces oil of moderate density and relatively high Sulphur content and is thereby referred to as medium sour crude oil. For this scenario, this assumption implies that crude oil that would normally be processed by the Richmond refinery could be rerouted to other West-Coast refineries. We don't know details about the origin of crude oil processed by individual refineries, but it is known that that non-Alaskan sources of medium sour feed West Coast refineries. Therefore, the assumption of substitution of crude oil from one source for another is not unreasonable.

The flow algorithm in NetFlow Dynamics includes parameters that specify the flexibility of facility operators to allow inventories of crude and refined products to deviate from normal levels, and of consumers to change the amount of fuel consumed, during stressing events. Assumptions about the behaviors of operators and consumers combine to influence how far and how fast impacts of a disruption propagate through a supply network. For this disruption scenario, for example, increasing the flexibility to change inventory levels could buffer the extent to which crude oil production on the North Slope is curtailed.

5 Future Work

The infrastructure description in the NTFM is intended to be continually improved as additional information becomes available, or in response to peer review. We expect that the Alaska addition will be improved as part of this process. In this sense, adding the Alaska portion of the network adds a long-term commitment to maintaining this part of the NTFM. This commitment will encourage users of the NTFM to be more aware of the details of ongoing developments in the Alaska petroleum industry.

As noted above, the NTFM has been used to simulate disruptions to present-day infrastructure. Another possible use of this type of model is informing analyses of future infrastructure developments. A part of the Alaska modeling effort that was not described in this report consists of building a prototype model that allowed future infrastructure and oil field developments to be added over simulated time. Such as model could be used, for example, to ensure that a proposed sequencing and scheduling of future developments would not result in periods during which flows on TAPS would fall below minimum required rates. Developing the prototype forward-looking Alaska model required changing some details of the computational approach. Although this effort did not advance beyond a development and testing phase, it provides a foundation for future efforts to develop a forward-looking petroleum model.

The West Coast transportation fuel market is increasingly interdependent with the broader Pacific region market. Participating in this broader market provides opportunities and competition for Alaska oil producers as well as West Coast refiners. One advantage of adding Alaska to the NTFM was separating Alaska crude oil received at West Coast ports from that received from other suppliers that ship in the Pacific Ocean. This allowed additional dynamics in the crude oil market to be represented in simulations. However, the rest of the Pacific shipments of oil and refined products remain aggregated in the NTFM. As the West Coast fuel market becomes increasingly impacted by developments in the Middle East, Australia, Singapore, China, and Russia, we see the potential benefit to NTFM users of disaggregating Pacific shipments to better represent the complex dynamics of the Pacific region.

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